Nuclear Target Cross Section Ratios at MINERvA

Brian G. Tice - Argonne National Laboratory

With travel support from Rutgers, The State University of New Jersey

How do we love MINERvA?
Let me count the ways*…

V Neutrino Physics

"I want to measure neutrino oscillations"

MINERvA will…

- help me understand neutrino energy reconstruction
- reduce my uncertainties from cross sections and nuclear effects

A Nuclear Physics

"I want to measure nucleon structure"

MINERvA will…

- use a probe sensitive to flavor and axial structure

*this is an incomplete list of the ways we love MINERvA

Priority: $\sigma(E_\nu)$
Neutrino-Nucleus Interactions

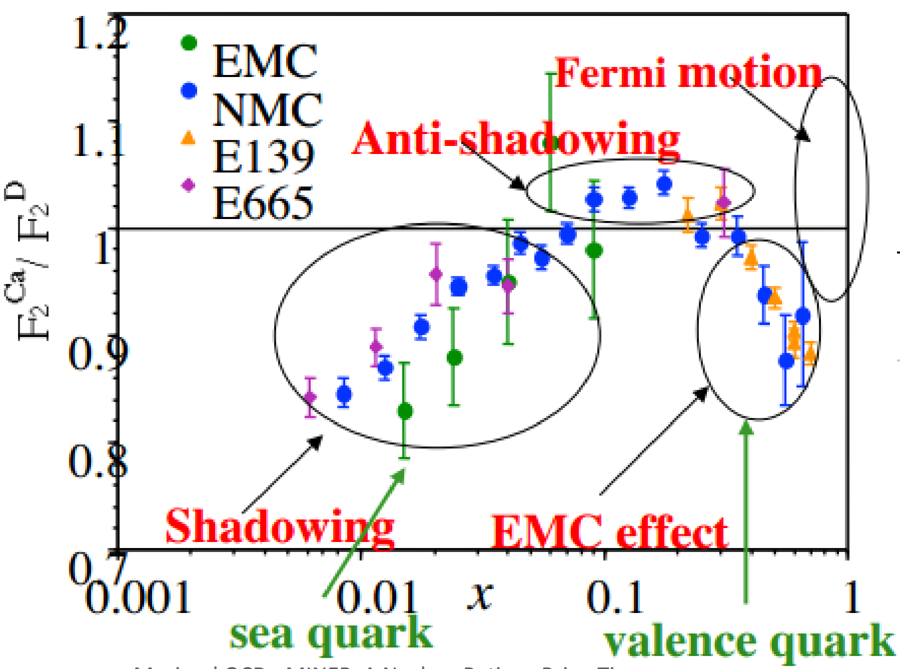
- Heavy nuclear targets used to get necessary statistics
  - Carbon, Iron, Lead, Water, Argon
- Nuclear effects are significant in neutrino scattering
  - Affects energy smearing and event rate
- Neutrino interaction simulation (models) rarely handle nuclear modifications well
  - They need data!

Must understand nuclear effects in neutrino scattering!

Priority: dσ/dx
Nuclear Effects

Charged lepton data show structure function F_2 effectively changes when nucleon bound in nucleus

μ/e – Ca Ratio



Physics Letters B
Volume 123, Issues 3–4, 31 March 1983, Pages 275–278

Abstract:
"Using the data on deep inelastic muon scattering on iron and deuterium the ratio of the nucleon structure functions $F_2(Fe)/F_2(D)$ is presented.
The observed x-dependence of this ratio is in disagreement with existing theoretical predictions. "

... much experimental and theoretical effort ...

CERN COURIER

Apr 26, 2013

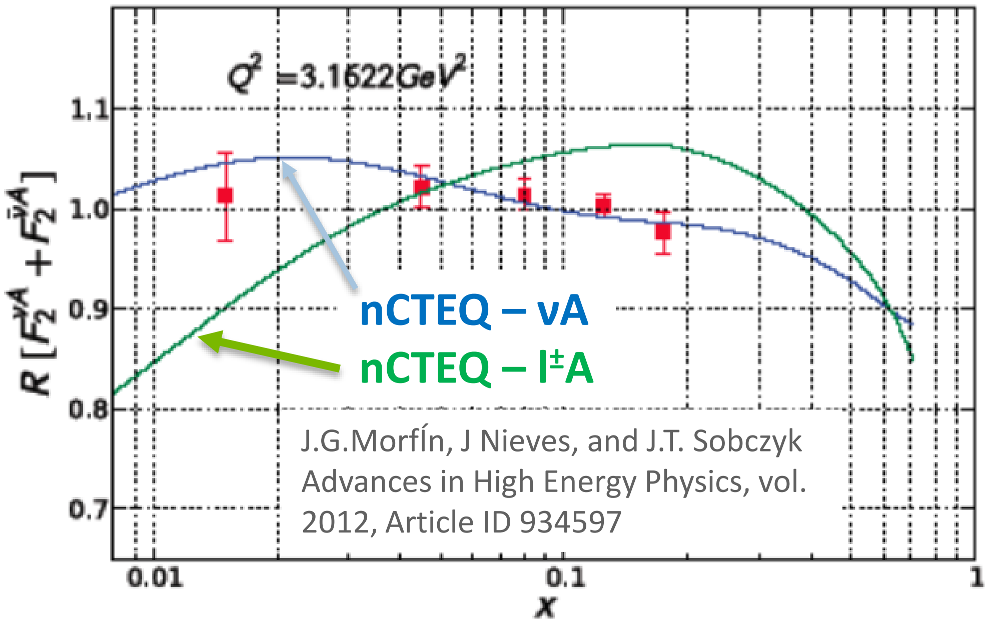
The EMC effect still puzzles after 30 years

Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

$$x = \frac{Q^2}{2M\nu}$$

Priority: dσ/dx
No comparable neutrino data!

Plot of ratio (R) of NUTEV (ν-Fe) data to theoretical predictions of free nucleon F_2. Compared to fits to ratio from charged lepton

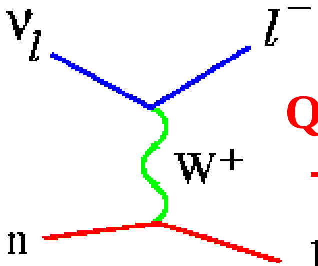


Expectations for neutrino nuclear structure function modification

- Neutrinos sensitive to structure function F_3
  - (Charged leptons are not)
  - Gives neutrinos ability to separate valence and sea
- Neutrinos sensitive to axial contribution of structure function F_2
  - (Charged leptons are not)
  - Axial effect larger at low x, low Q^2

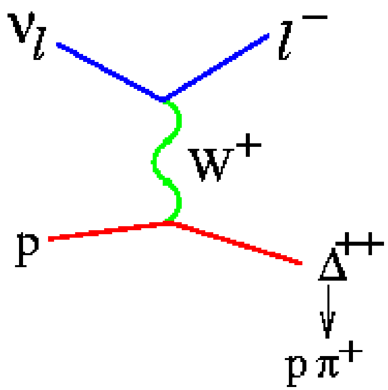
$$x = \frac{Q^2}{2M\nu}$$

Inclusive Neutrino Cross Sections

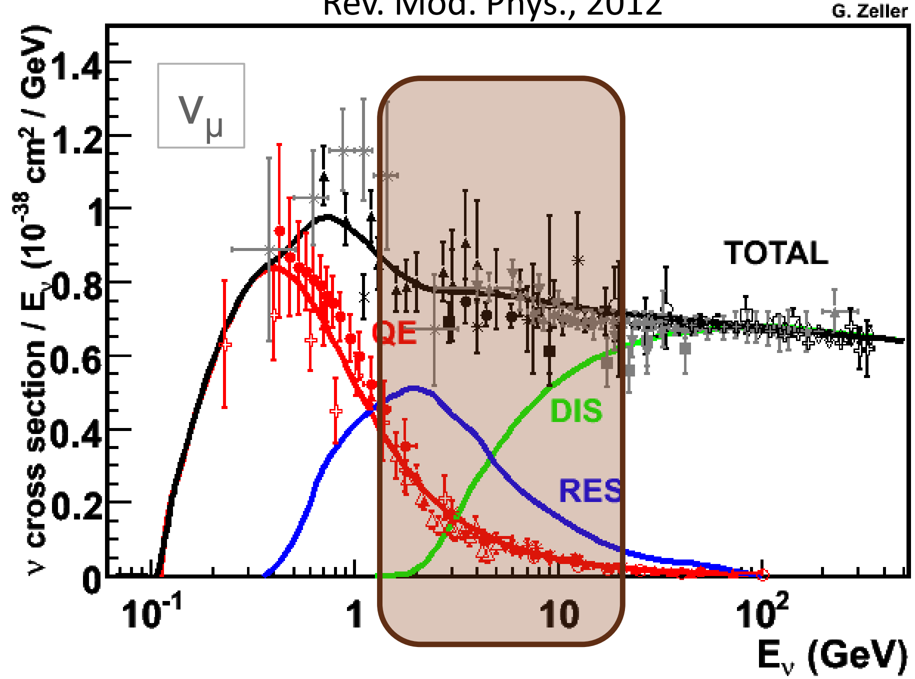


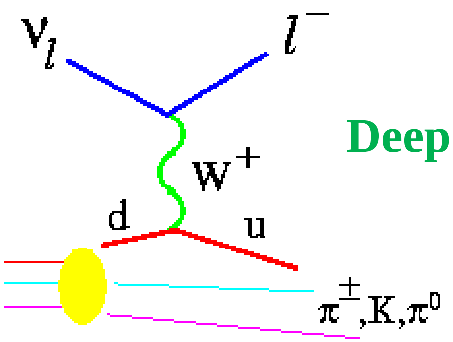
Quasi-Elastic (CCQE)
-knock out nucleon-

Resonance Production (Res)
-excite nucleon-



J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys., 2012



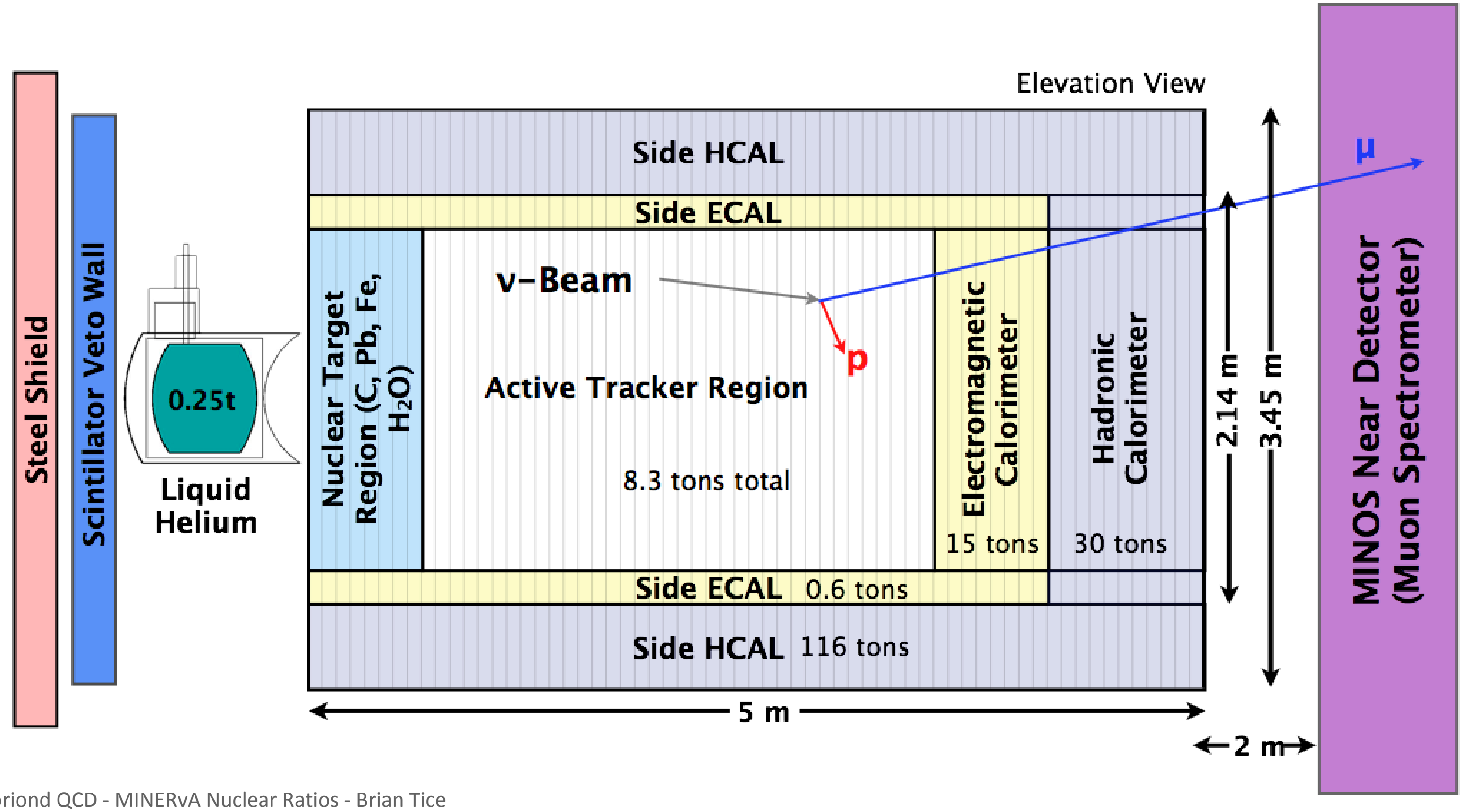


Deep Inelastic Scattering (DIS)
-destroy nucleon-

MINERvA Detector (again)

The MINERvA Detector
Calibration and Performance
arXiv:1305.5199 [physics.ins-det]

- 120 modules for tracking and calorimetry (~32k readout channels)
  - Active element is polystyrene (plastic scintillator)
- Construction completed Spring 2010. He and Water added in 2011
- Magnetized MINOS Near Detector serves as toroidal muon spectrometer



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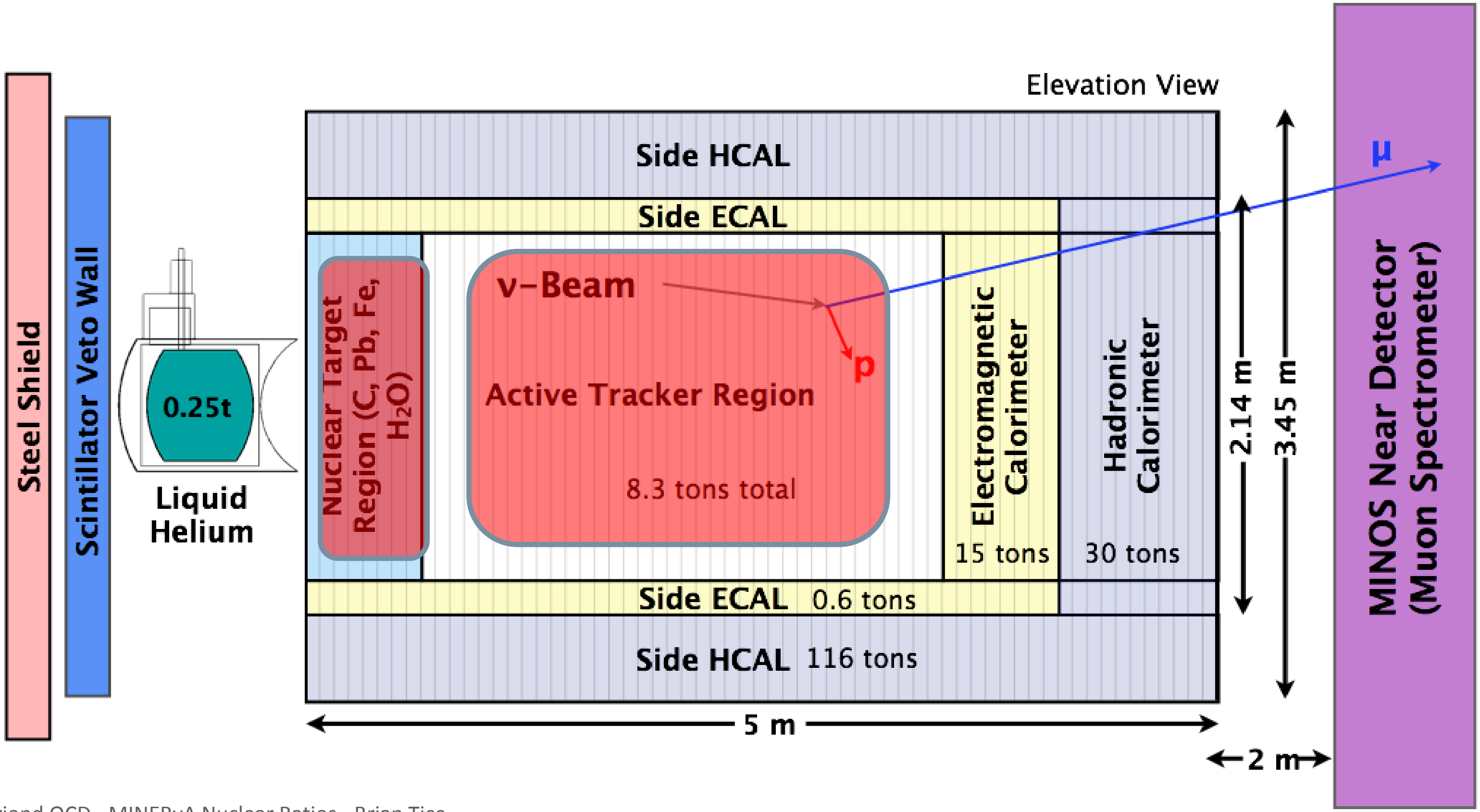
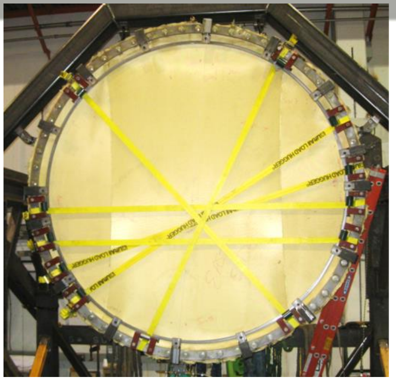
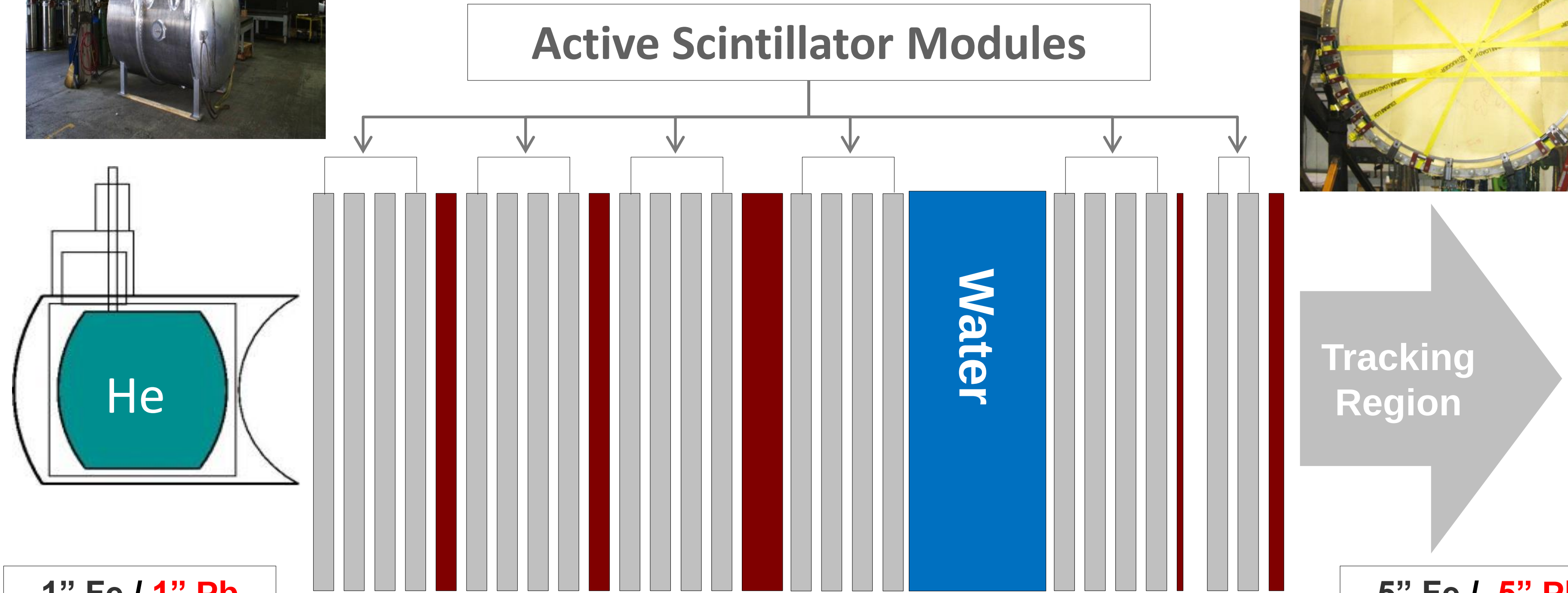


250 kg
Liquid He

500kg
Water

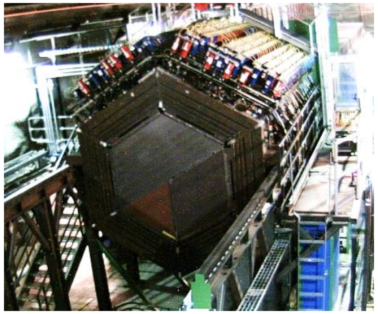




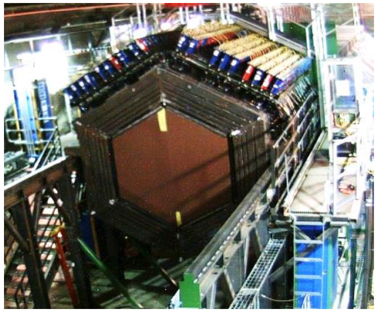
1” Fe / 1” Pb
323kg / 264kg

1” Pb / 1” Fe
266kg / 323kg

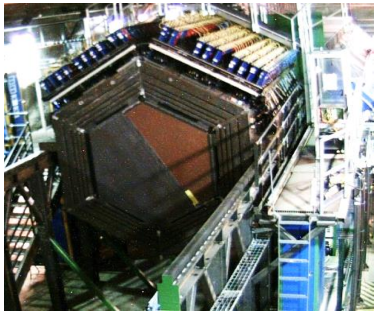
3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg



0.3” Pb
228kg

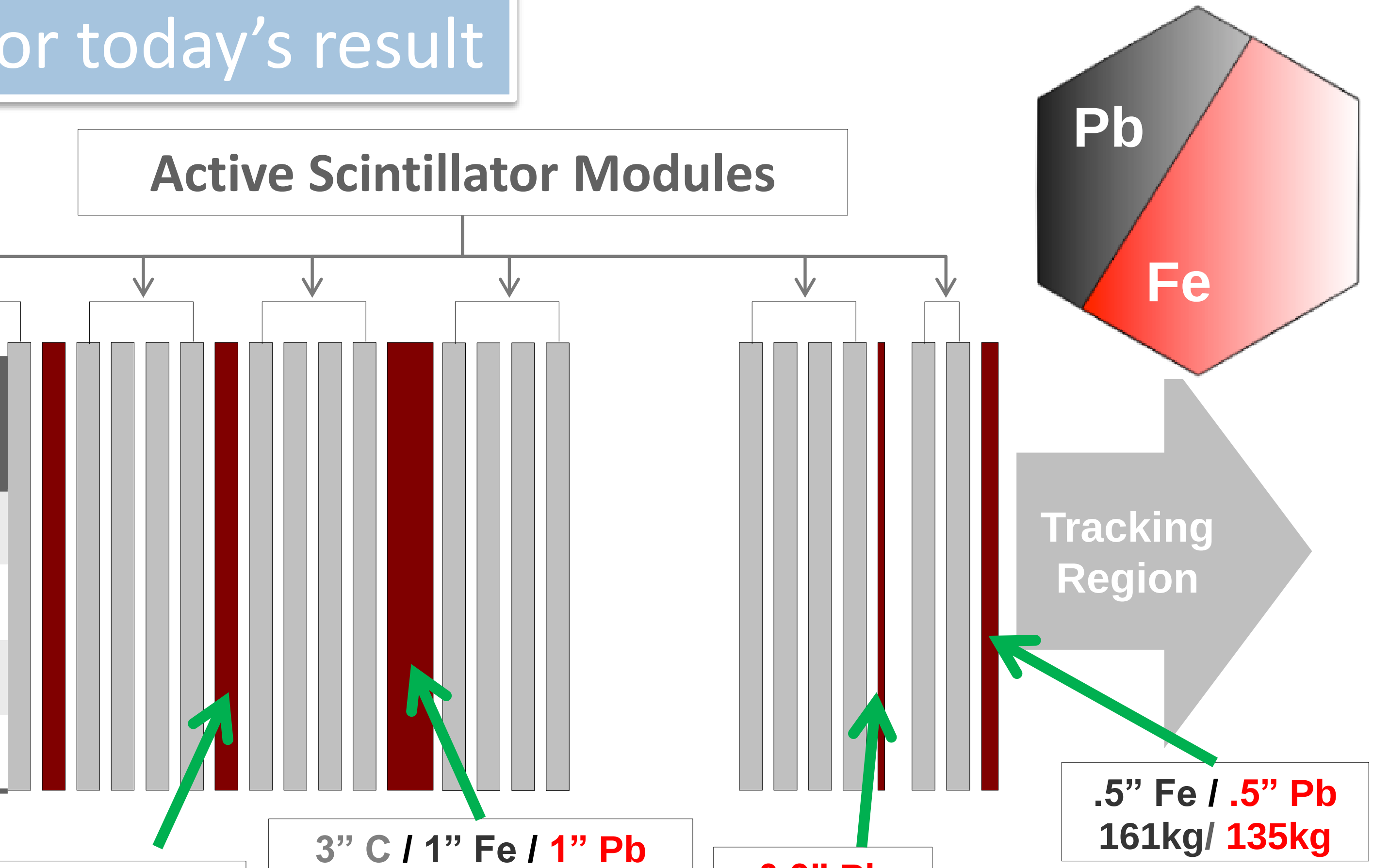


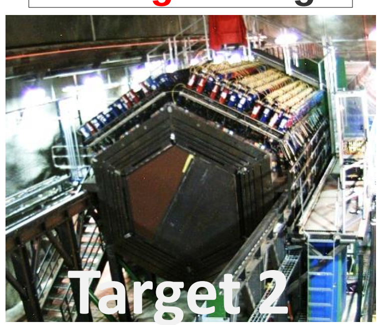
.5” Fe / .5” Pb
161kg/ 135kg

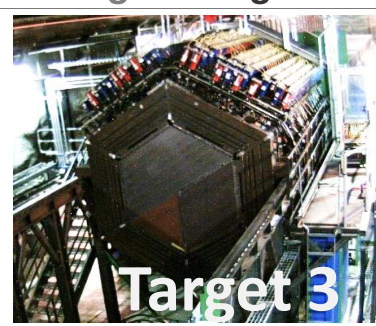


Targets used for today's result

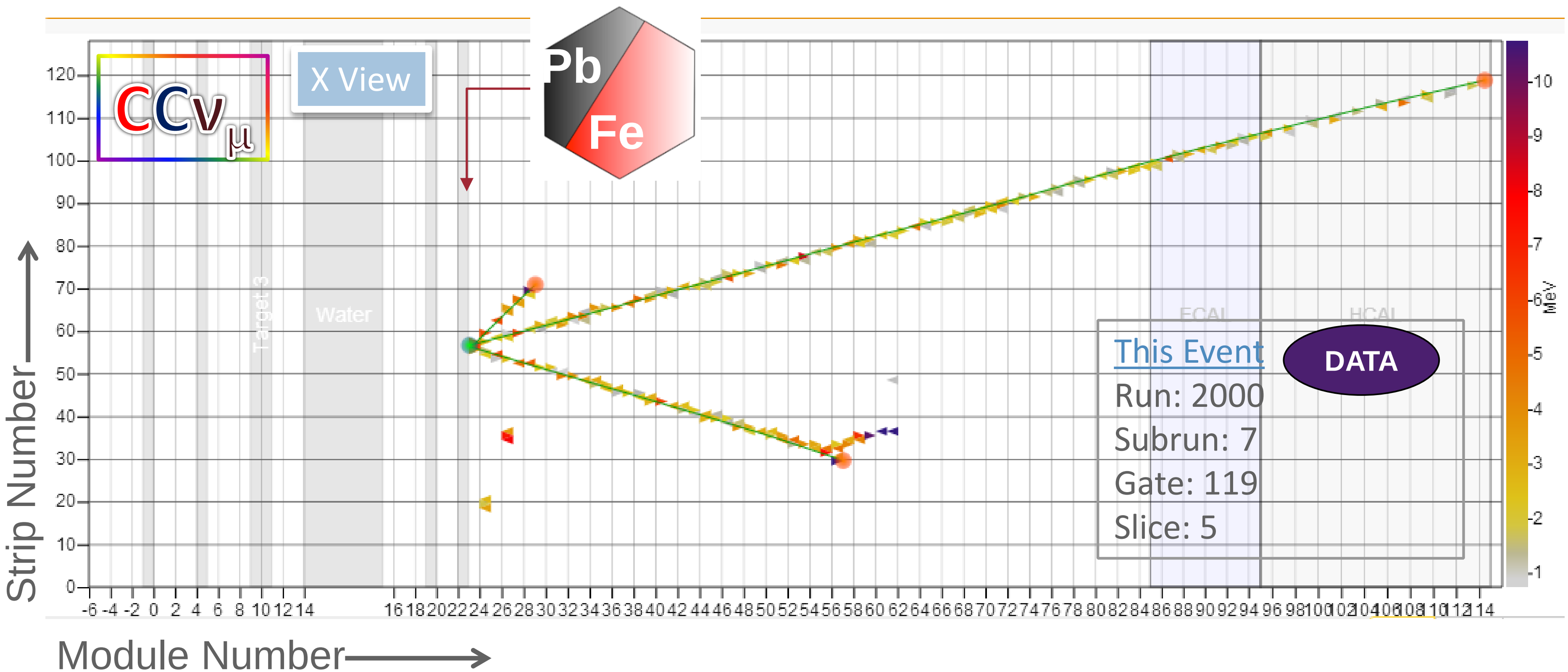
A	Mass (t)	Events
C	0.16	6k
Fe	0.63	19k
Pb	0.71	24k
CH	5.48	189k







Event Selection



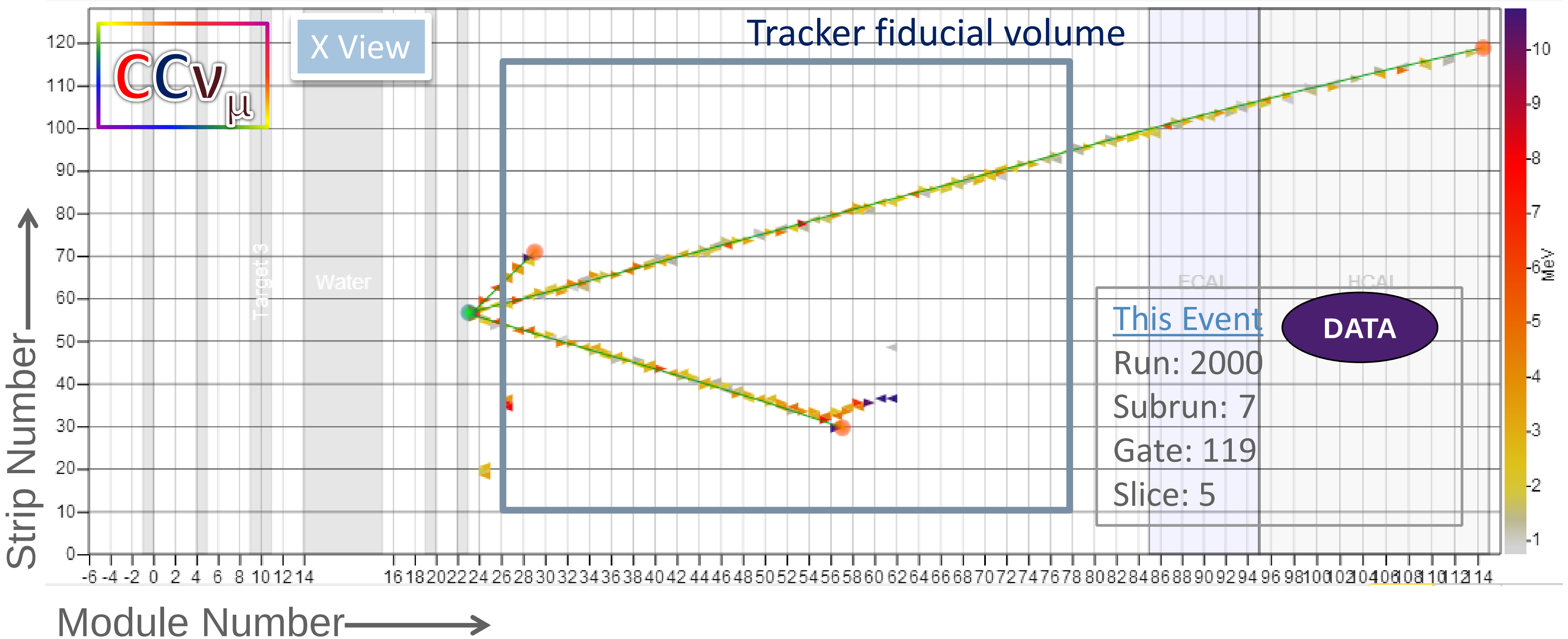
Event Topology

Muon must be matched to a momentum- and charge-analyzed track in MINOS ND

Interaction Material

Vertex must be in passive nuclear target or adjacent scintillator plane

Event Selection



Event Topology

Muon must be matched to a momentum- and charge-analyzed track in MINOS ND

Interaction Material

Scintillator events must be in the fiducial volume of the tracker

Event Reconstruction

Hadronic Energy

Sum of non-muon visible energy.

Weight for passive material traversed.

$$\nu = E_{recoil} = \alpha \times \sum_{i}^{hits} \frac{E_i}{f_i}$$

Muon Energy

From range or curvature in MINOS.

Add energy lost in MINERvA.

Muon Angle

Fitted track slopes at vertex.

$$\boxed{E_\nu = \nu + E_\mu}$$

Unfold neutrino energy distributions

Use simulation of detector smearing

$$\boxed{x = \frac{Q^2}{2M\nu}}$$

Do not unfold x distributions

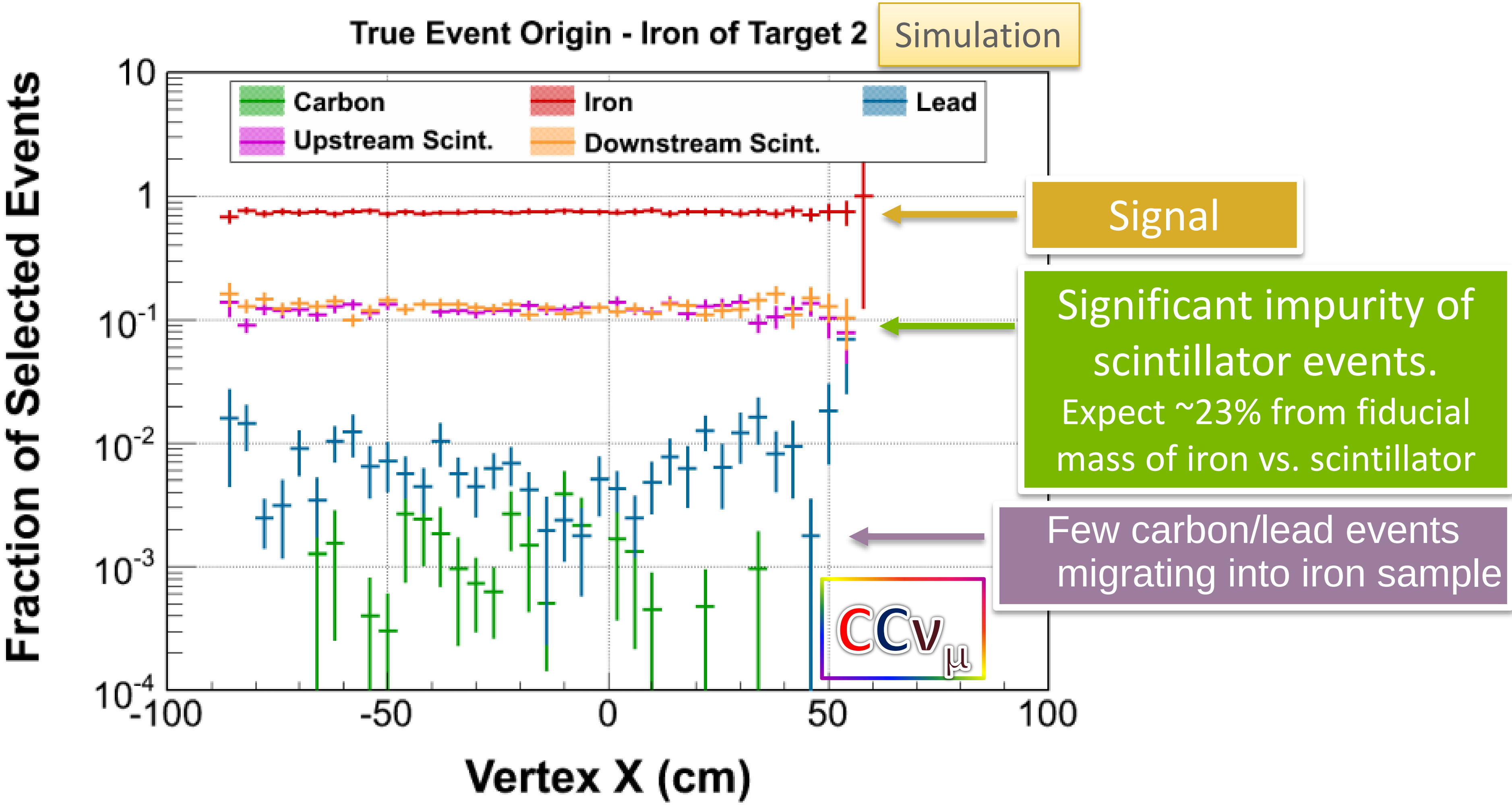
Large migration among x bins

Avoid systematic effects

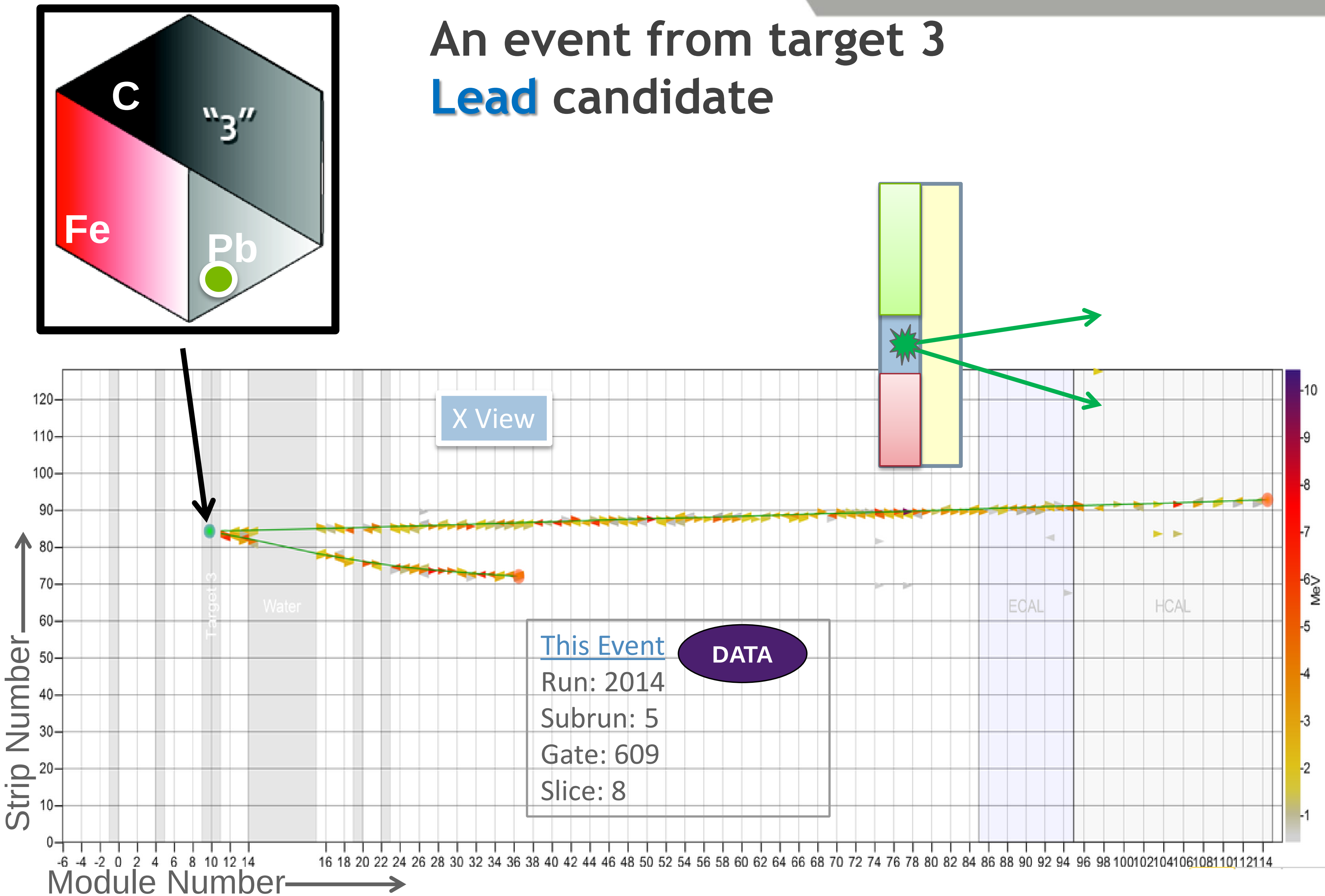
$$\boxed{Q^2 = 2E_\nu \left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right)}$$

Major Background - Misidentified Nucleus

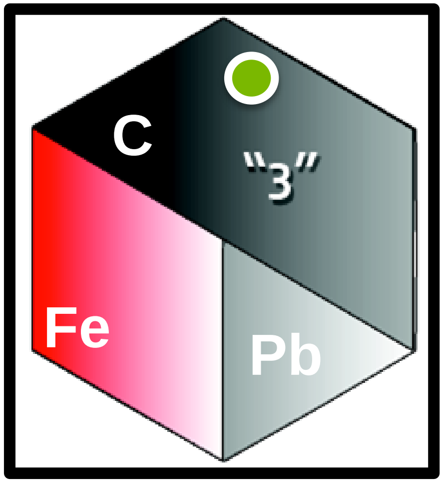
Background from other sources < 1%

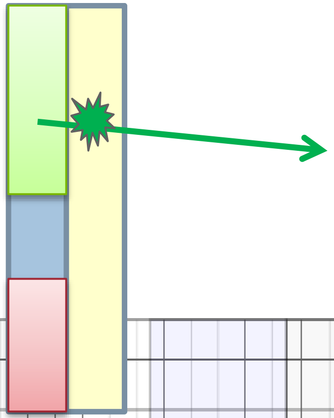


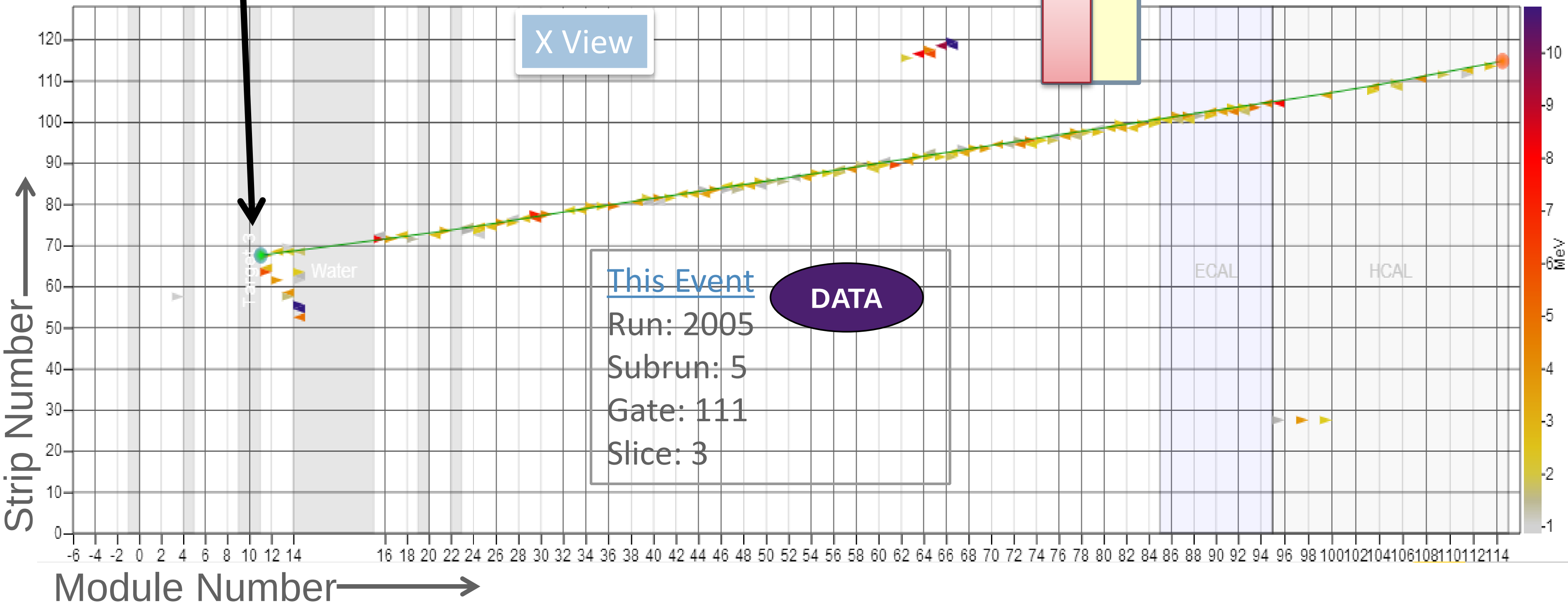
An event from target 3
Lead candidate



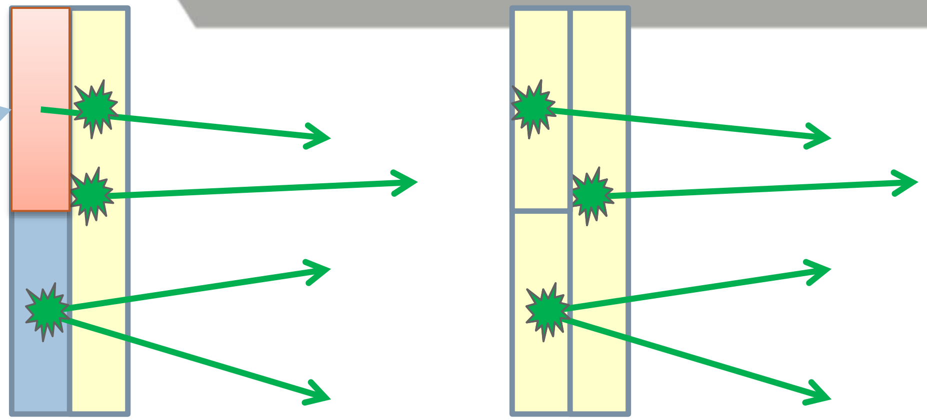
An event from target 3
Carbon candidate

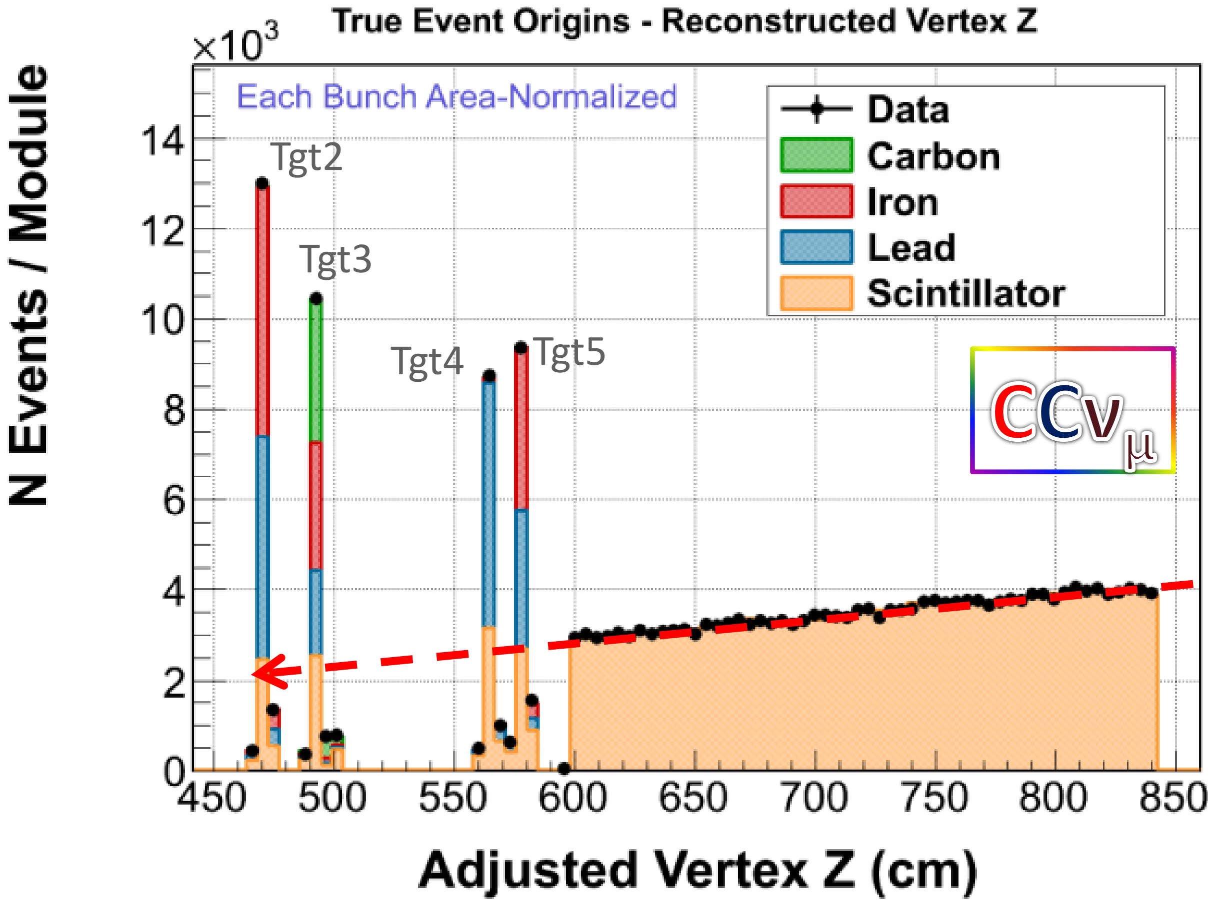






One track events from passive target have a vertex in the first plane downstream of the target

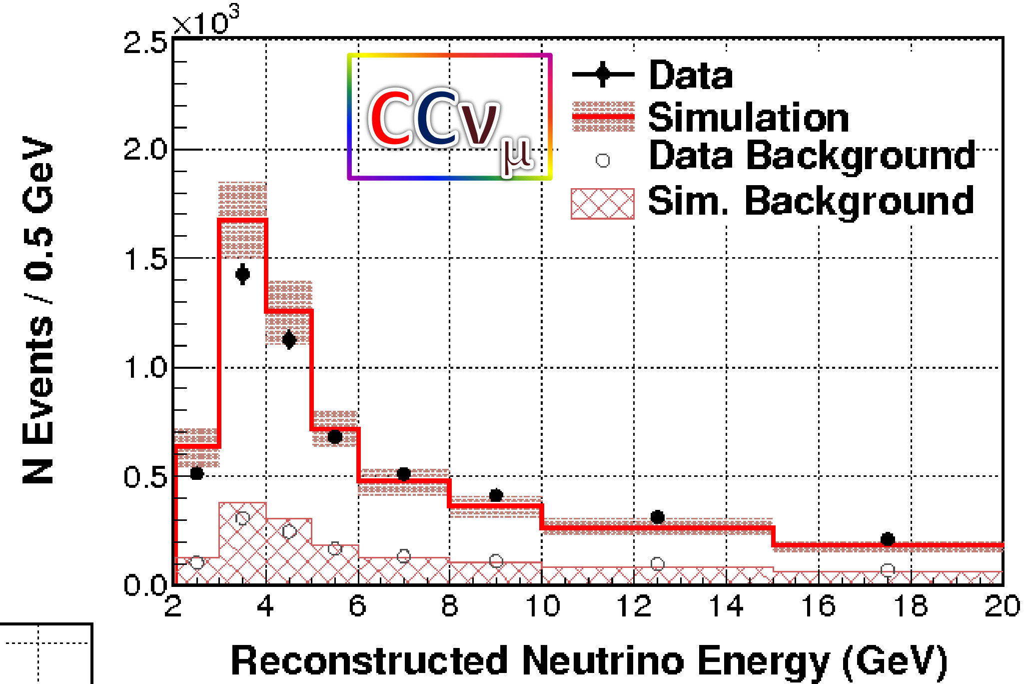


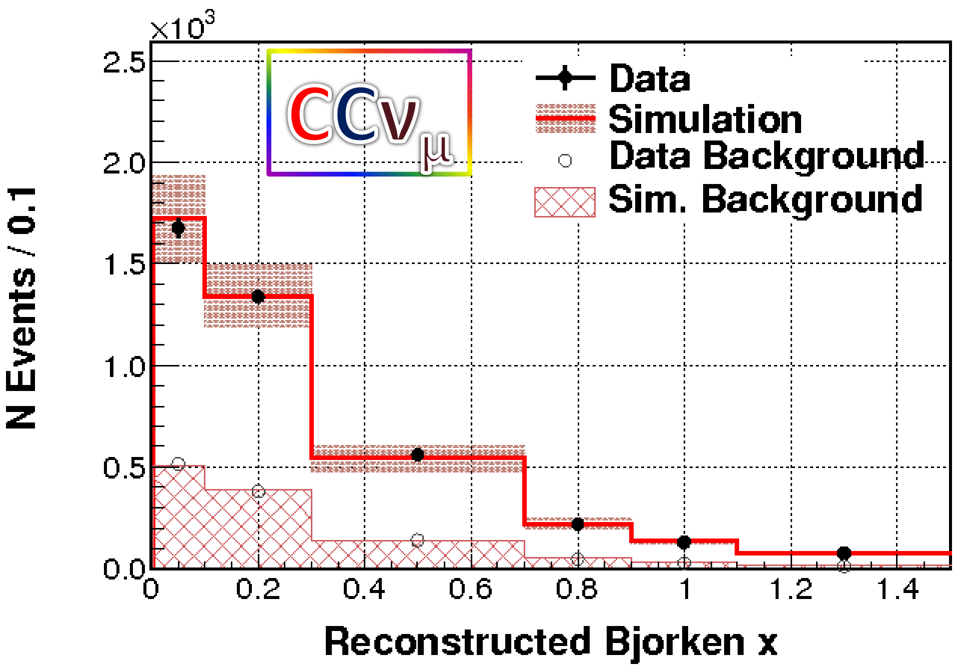


Tracking region used to estimate and subtract contamination from scintillator events

Event distributions in Fe of Target 5

A separate estimated background for **data** and **Simulation**

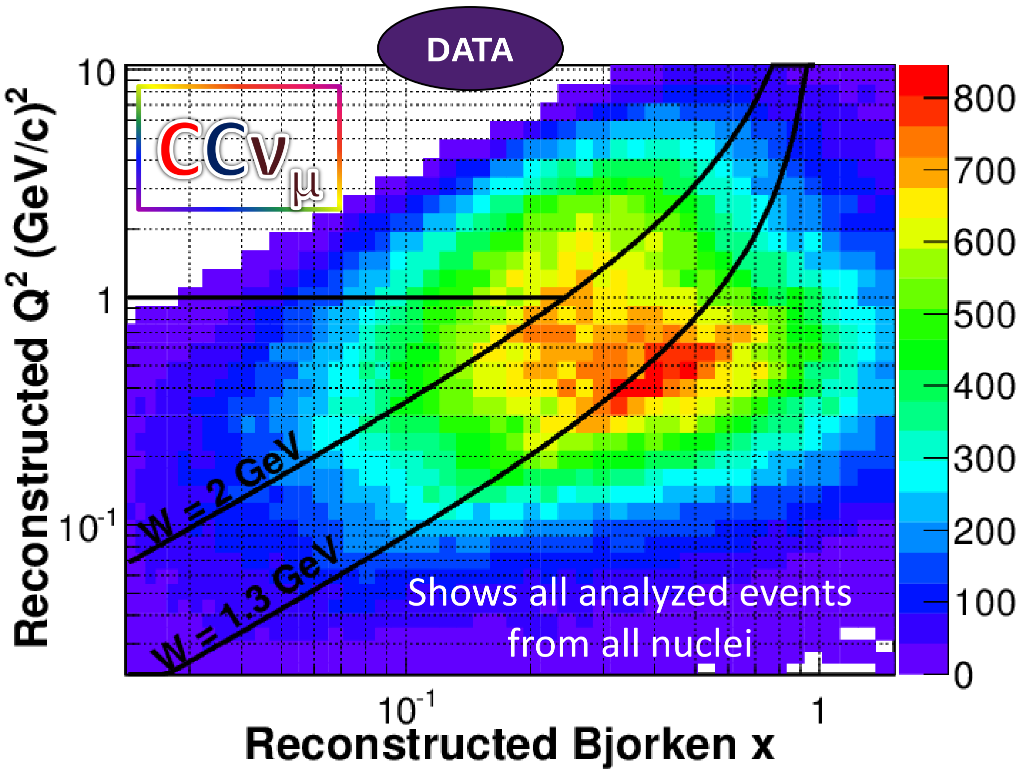


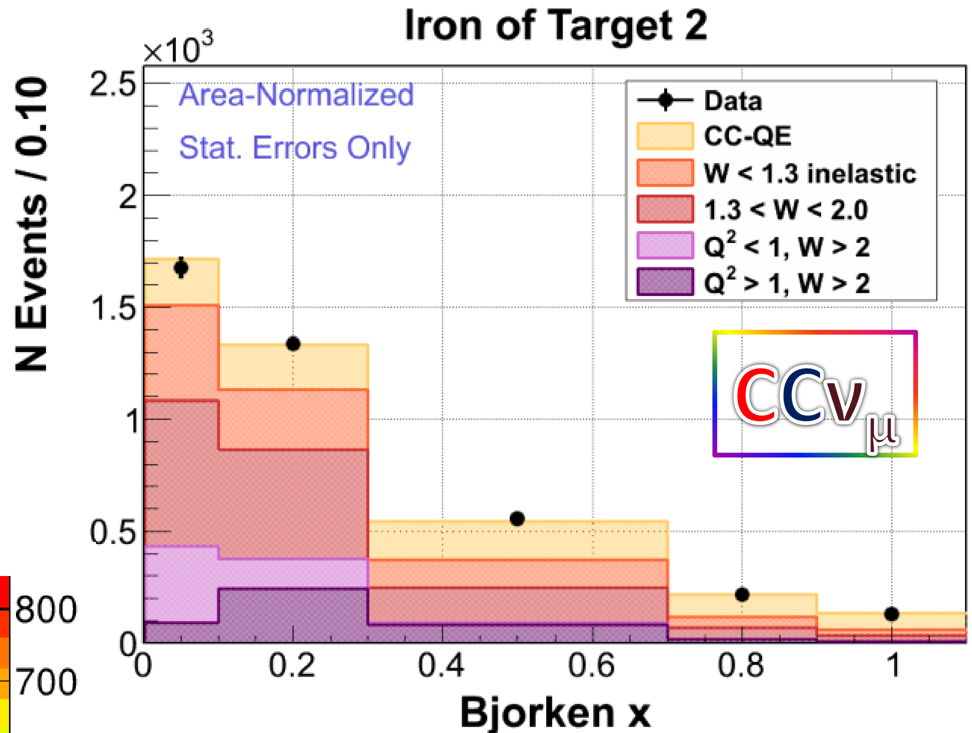


Simulation scaled to data by total number of events passing selection.
Shading on simulation is systematic uncertainty.

Kinematic Space

Event sample is a blend of interaction channels

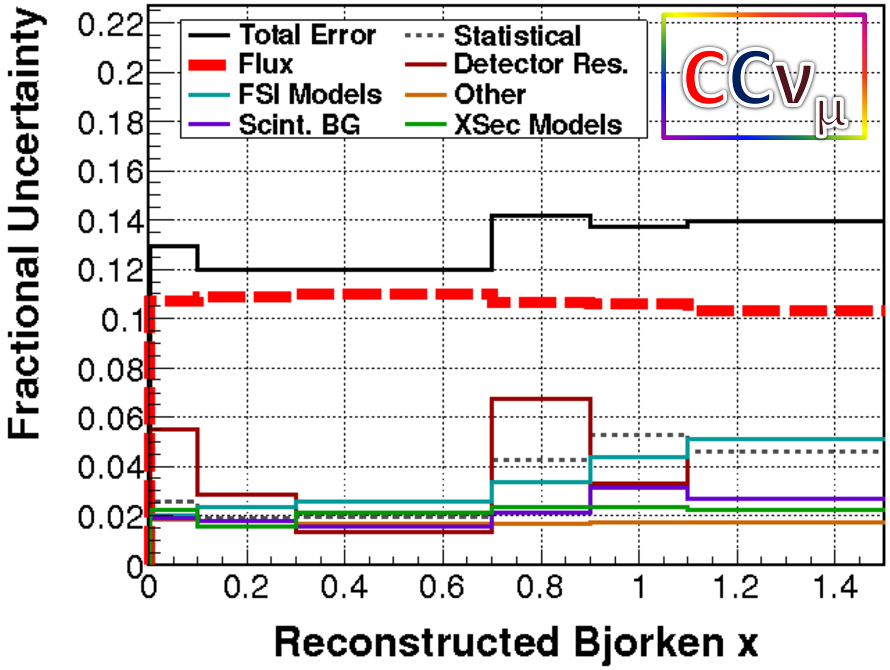




Invariant hadronic mass

$$W = \sqrt{M^2 + 2M\nu - Q^2}$$

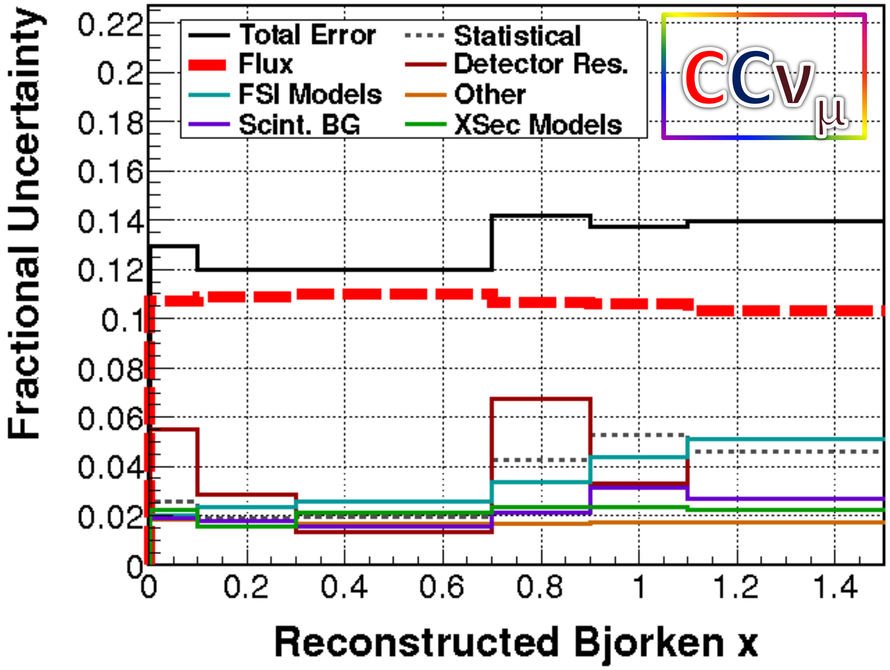
Errors on Absolute Cross Section



Flux is dominant systematic

$d\sigma^{Fe}/dx$

Errors on Absolute Cross Section



$$\frac{\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\boxed{\Phi}T)\Delta x_i}}{\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\boxed{\Phi}T)\Delta x_i}}$$

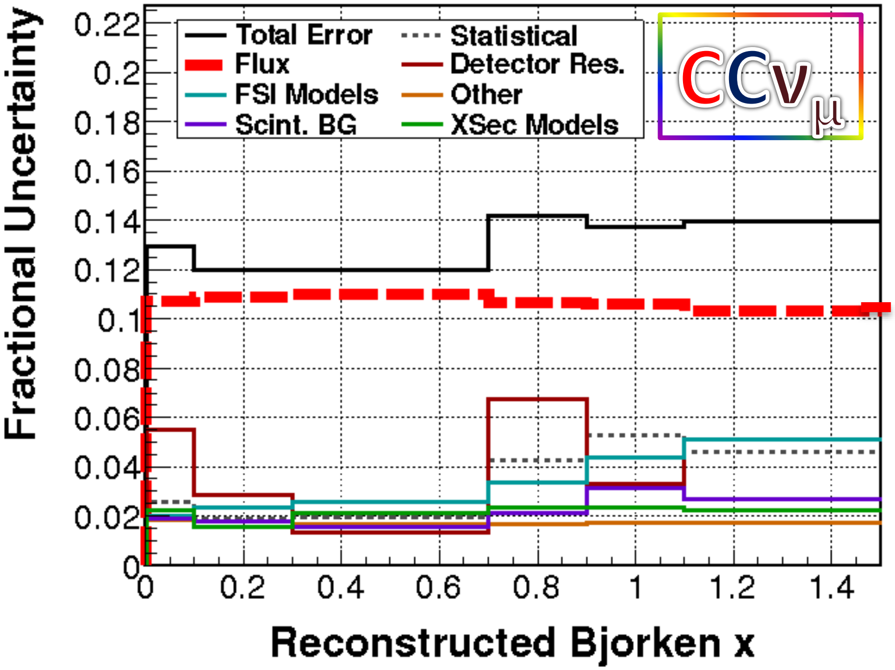
Flux is the same throughout detector

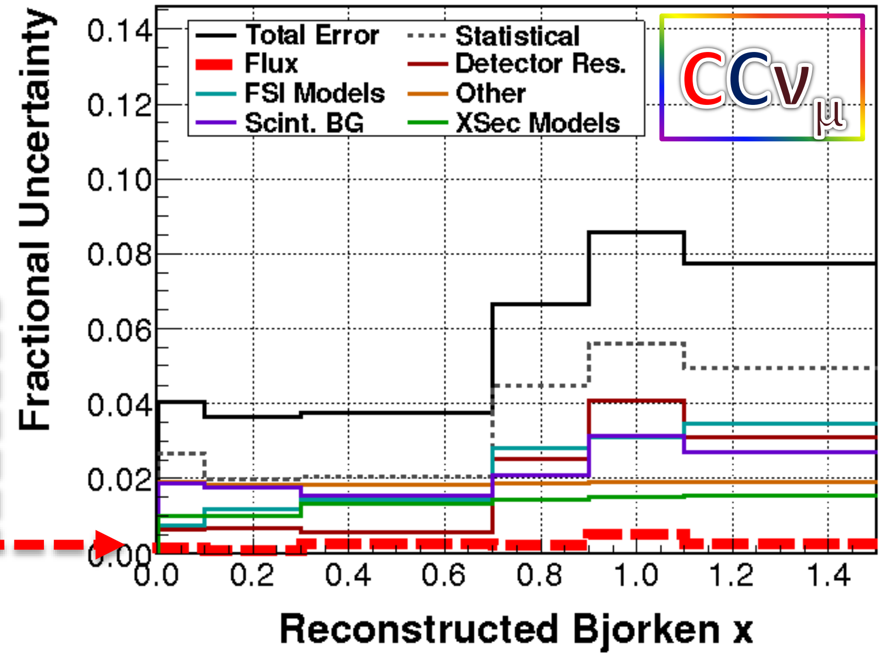
$d\sigma^{Fe}/dx$

Take ratio of cross sections to ~cancel flux

Errors on Absolute Cross Section

Errors on Ratio of Cross Sections





$d\sigma^{Fe}/dx$

$$\frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx}$$

Results

$CC\nu_\mu$

Charged-Current Inclusive Ratios of Cross Sections

Signal Kinematics

2 < Neutrino Energy < 20 GeV

0 < Muon Angle < 17 deg

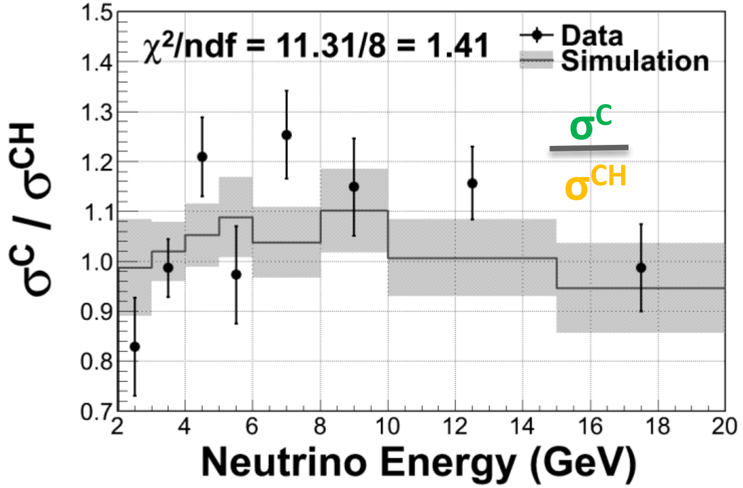
Neutrino Energy

$$\frac{\sigma^{C}}{\sigma^{CH}} \qquad \frac{\sigma^{Fe}}{\sigma^{CH}} \qquad \frac{\sigma^{Pb}}{\sigma^{CH}}$$

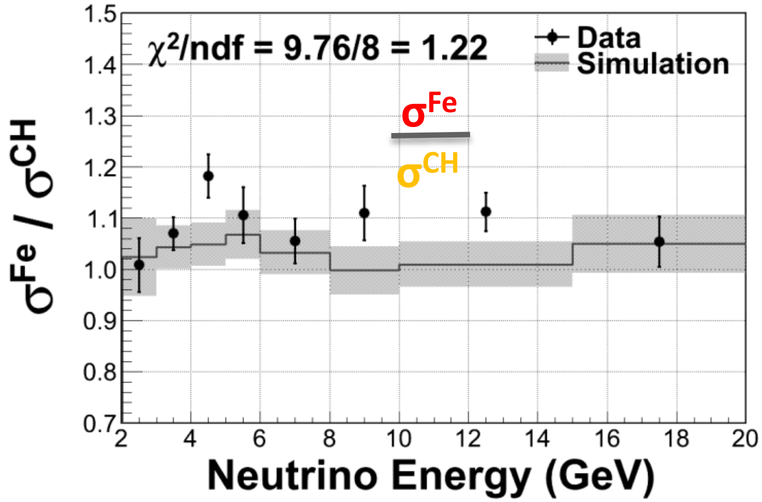
Bjorken x

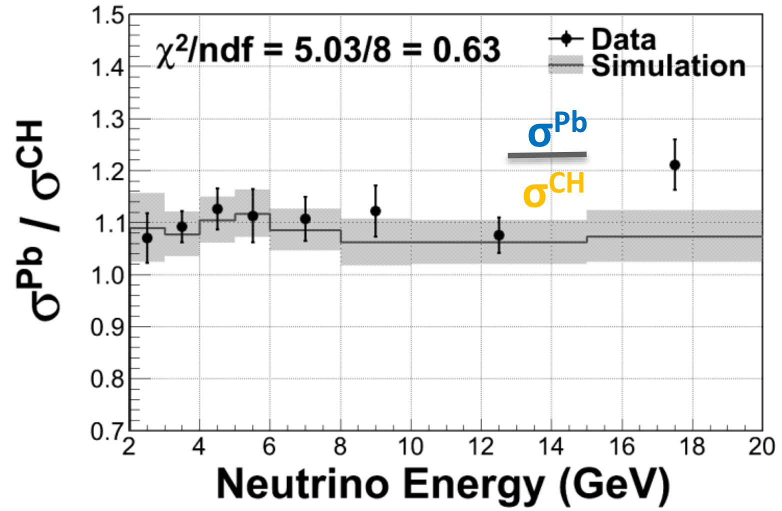
$$\frac{d\sigma^{C}/dx}{d\sigma^{CH}/dx} \qquad \frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx} \qquad \frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}$$

Neutrino Energy



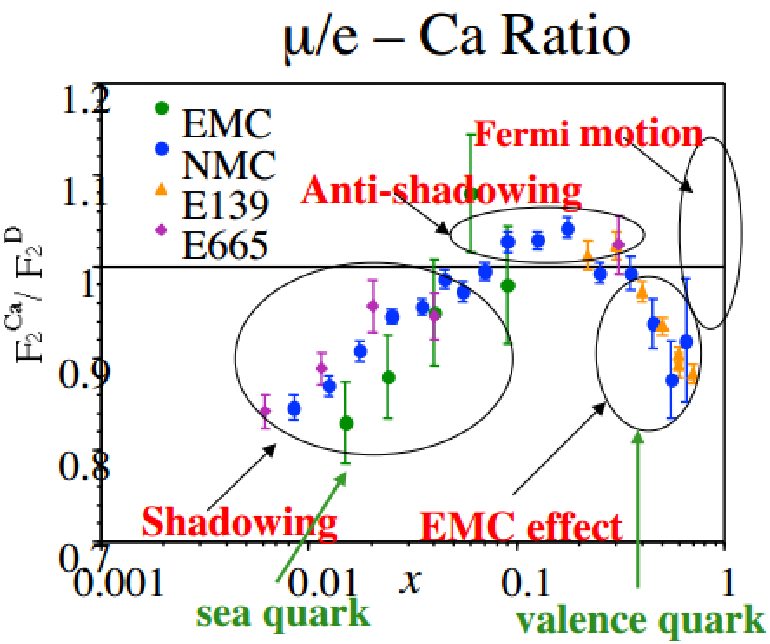
- No evidence of tension between our data and simulation here
  - Good news for oscillation experiments so far…

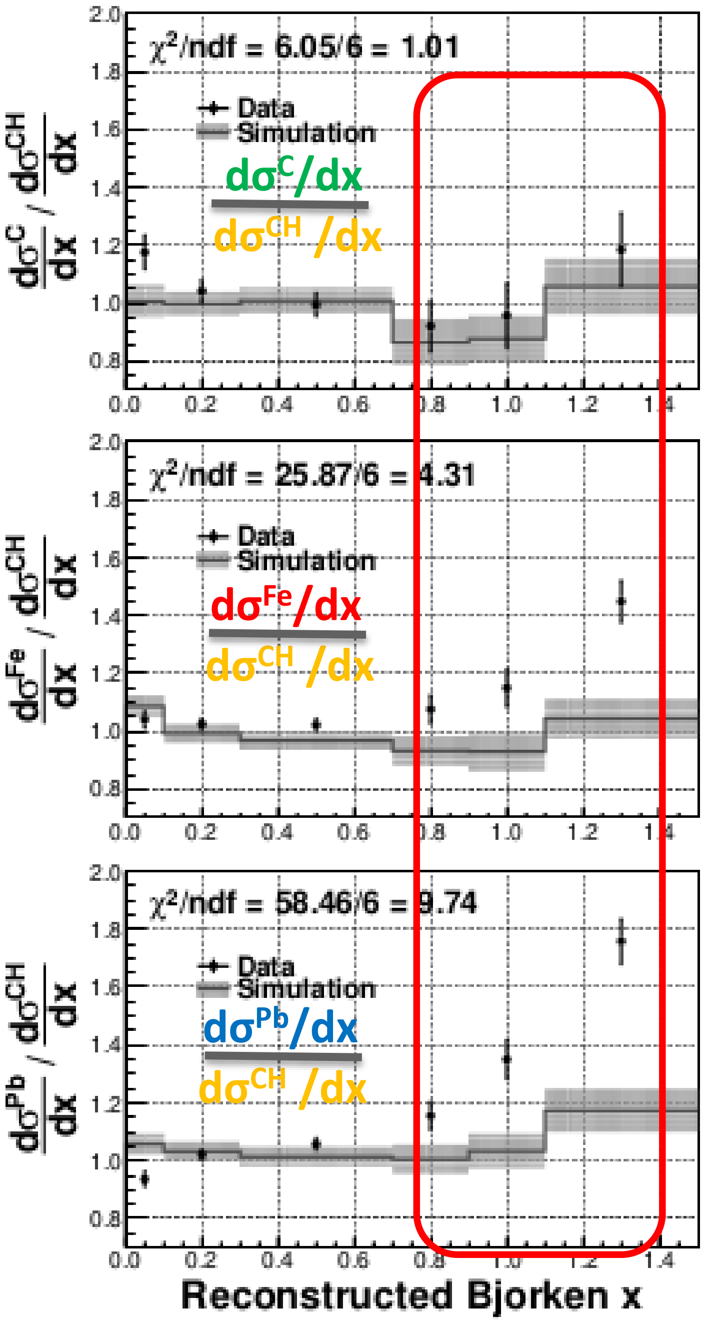




High x

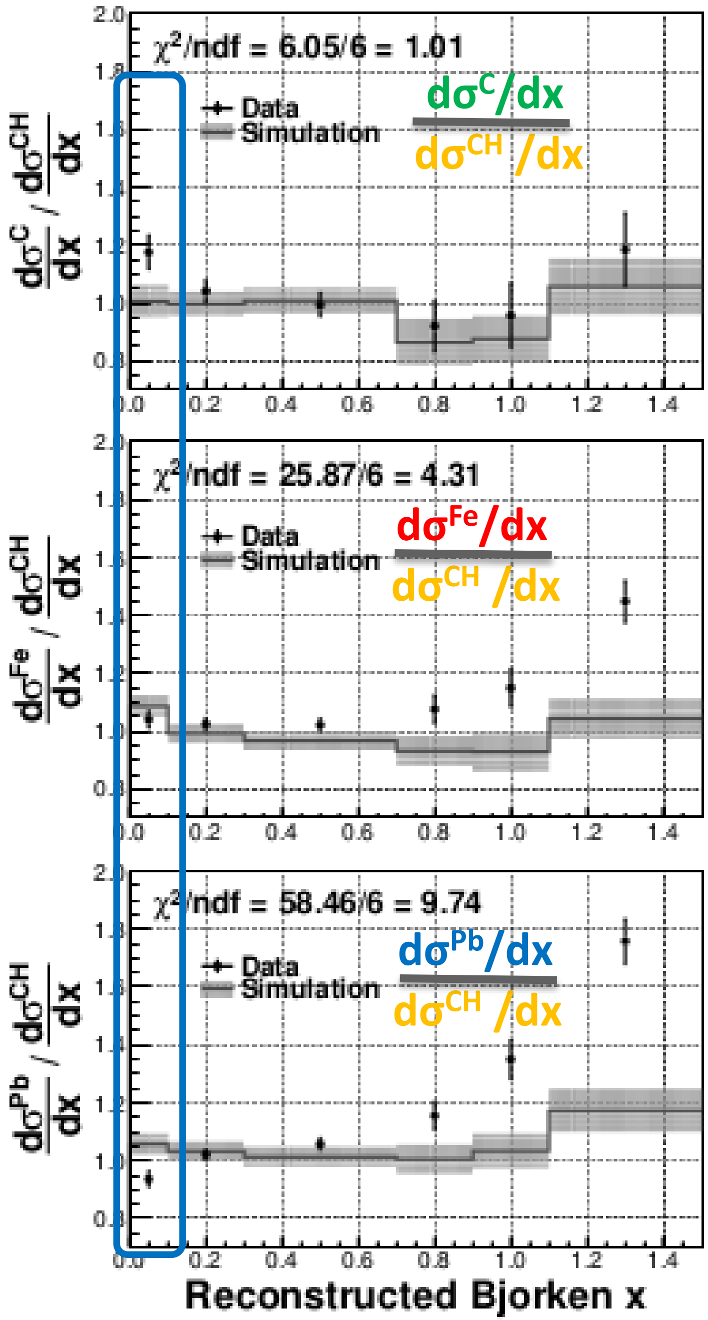
- At x=[0.7,1.5], we observe a **excess** that grows with the size of the nucleus
- This effect is not observed in simulation





Low x

- At x=[0*,0.1], we observe a **deficit** that increases with the size of the nucleus
- This effect is not modeled in simulation



Expected Neutrino Differences

Neutrinos sensitive to structure function xF_3

Neutrinos sensitive to axial piece of structure function F_2

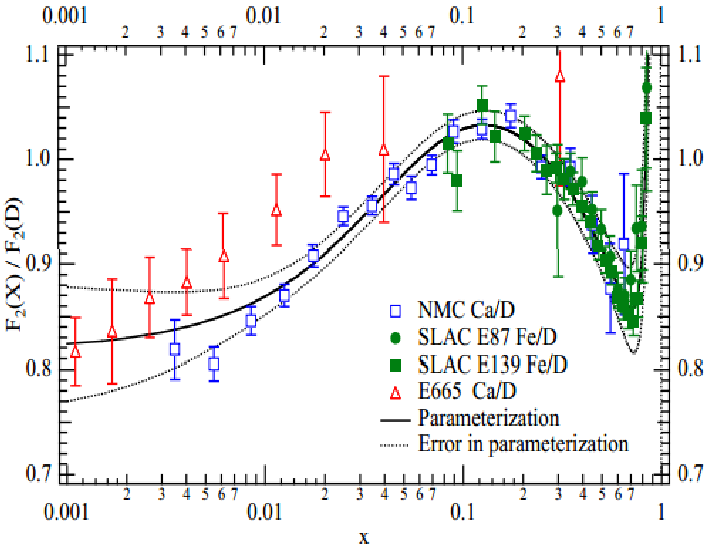
* Simulation suggests events down to 0.005
No events really at 0

Simulations of Nuclear Modification

Our Simulation | GENIE 2.6.2

- Bodek-Yang Model (2003)
- Fit to charged lepton data
- All nuclei have same modification
  - All treated as isoscalar iron

A. Bodek, I. Park, and U.-K. Yang,
Nucl. Phys. Proc. Suppl. 139, 113 (2005)



Compare to Other Models

Differ by only < 1%

S. A. Kulagin and R. Petti, Nucl. Phys. A 765, 126 (2006)
S. A. Kulagin and R. Petti, Phys. Rev. D 76, 094023 (2007)
A. Bodek, U. K. Yang arXiv:1011.6592 (2013)

- Kulagin-Petti (KP)
  - Microphysical model
  - Starts with neutrino-nucleon F1, F2, F3
  - Incorporates A-dependent effects
- Bodek-Yang 2013(BY)
  - Similar to GENIE
  - Specific fits for C, Fe, Pb

x	C/CH G	C/CH σ_{st} %	C/CH KP Δ%	C/CH BY Δ%	Fe/CH G	Fe/CH σ_{st} %	Fe/CH KP Δ%	Fe/CH BY Δ%	Pb/CH G	Pb/CH σ_{st} %	Pb/CH KP Δ%	Pb/CH BY Δ%
0.0–0.1	1.050	1.0	0.3	0.0	1.011	0.5	-0.4	1.2	1.037	0.5	-1.5	0.8
0.1–0.3	1.034	0.7	-0.3	0.0	1.017	0.3	-0.7	-0.5	1.071	0.3	-1.0	-0.7
0.3–0.7	1.049	0.8	-0.1	0.0	1.049	0.4	0.0	0.0	1.146	0.4	0.4	0.6
0.7–0.9	1.089	1.8	-0.1	0.0	0.995	0.9	0.4	0.1	1.045	0.9	0.1	0.7
0.9–1.1	1.133	2.3	-0.1	0.0	0.948	1.1	0.2	0.0	0.985	1.1	0.2	0.2
1.1–1.5	1.111	2.2	0.0	0.0	0.952	1.1	0.0	0.0	1.036	1.1	0.1	0.0

Conclusions

- First results from nuclear targets in MINERvA
- First precise direct measurement of nuclear dependence of neutrino cross sections in the few-GeV regime
- Result submitted to PRL. Find it at arXiv:1403.2103

CCν_μ

Measurement of Ratios of ν_μ Charged-Current Cross Sections on C, Fe, and Pb to CH at Neutrino Energies 2–20 GeV

- Our data are not reproduced by simulation
  - Available models differences are small compared to discrepancy
- Oscillation experiments should consider discrepancies in systematics

- More theoretical work is needed to improve models of neutrino-nucleus scattering in all kinematic regions

Backup

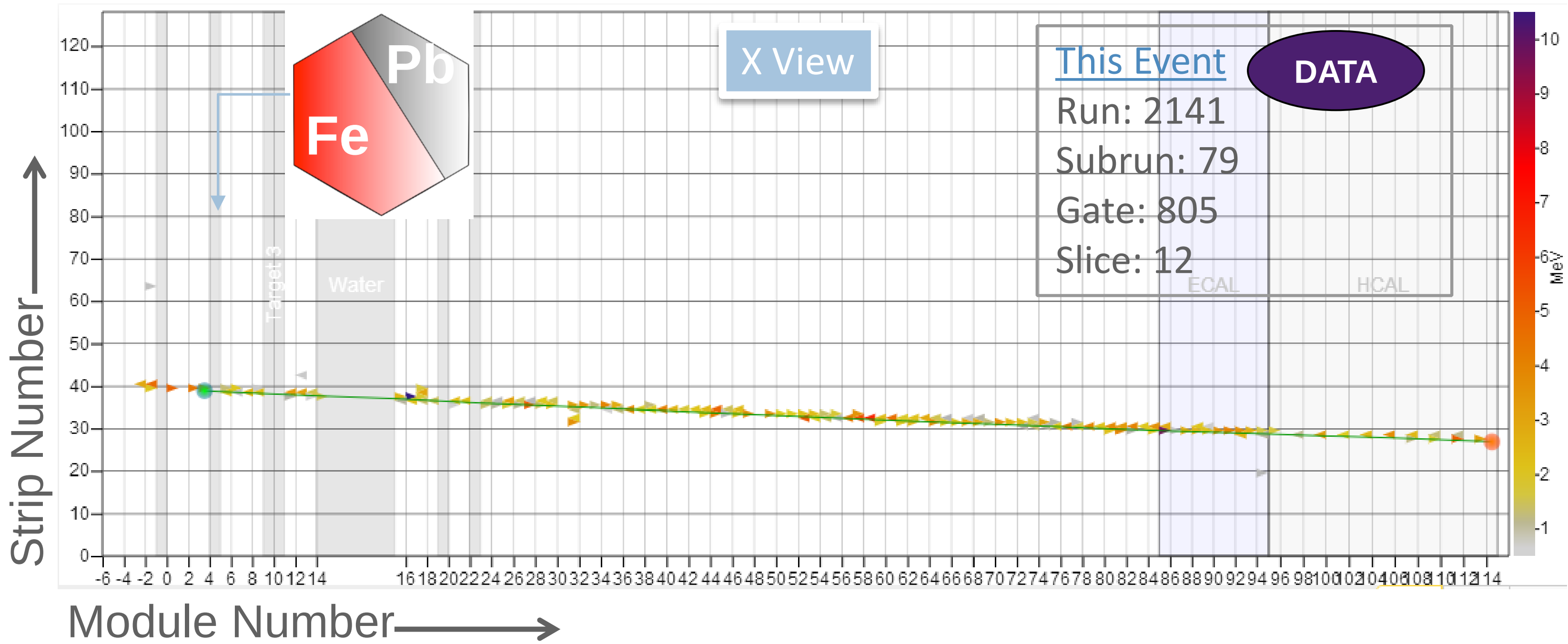
Background - Rock Muons

Affected only Target 2 in the earliest data

Uninstrumented planes reduced tracking efficiency. Veto wall was not installed yet.

Target 2 ≈ 50% of iron, 33% of lead. Early data ≈ 30% of all neutrino data.

→ < 1% flat correction

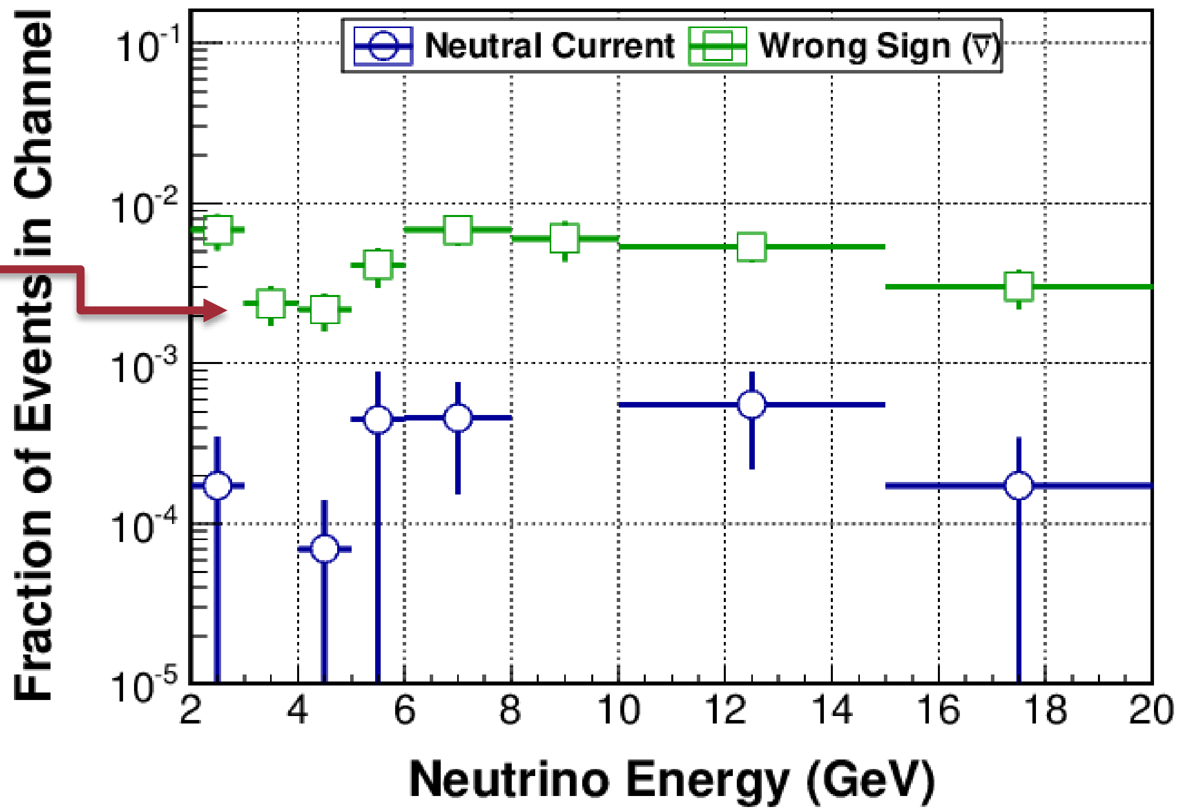


Background - Neutral Current and $\overline{\nu}_{\mu}$ Events

Small backgrounds (<0.5%)

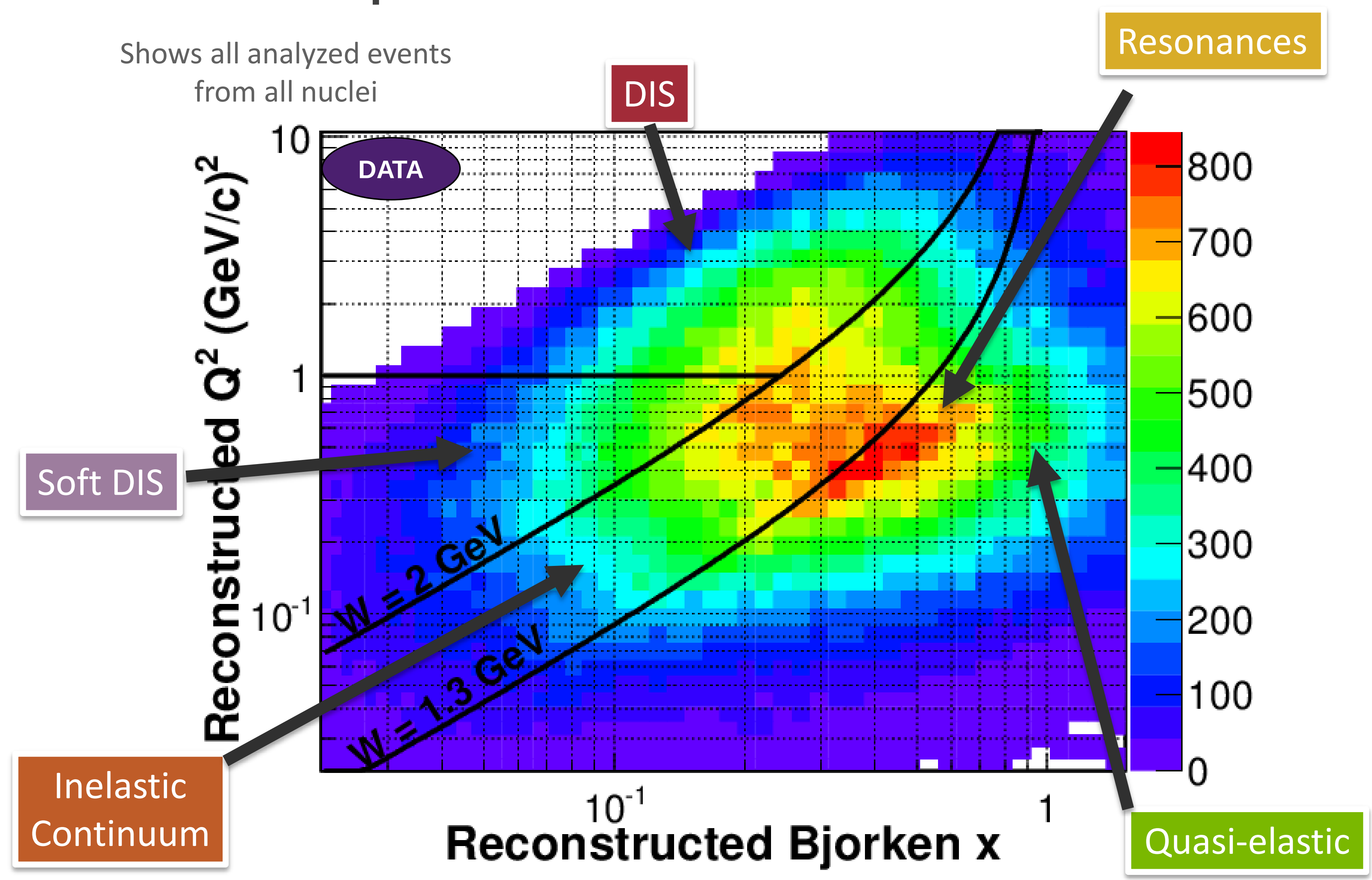
Subtract using simulation prediction for fractional background

Wrong sign contamination is smaller in the beam's focusing beam



Kinematic Space

Shows all analyzed events from all nuclei



Forming a Cross Section

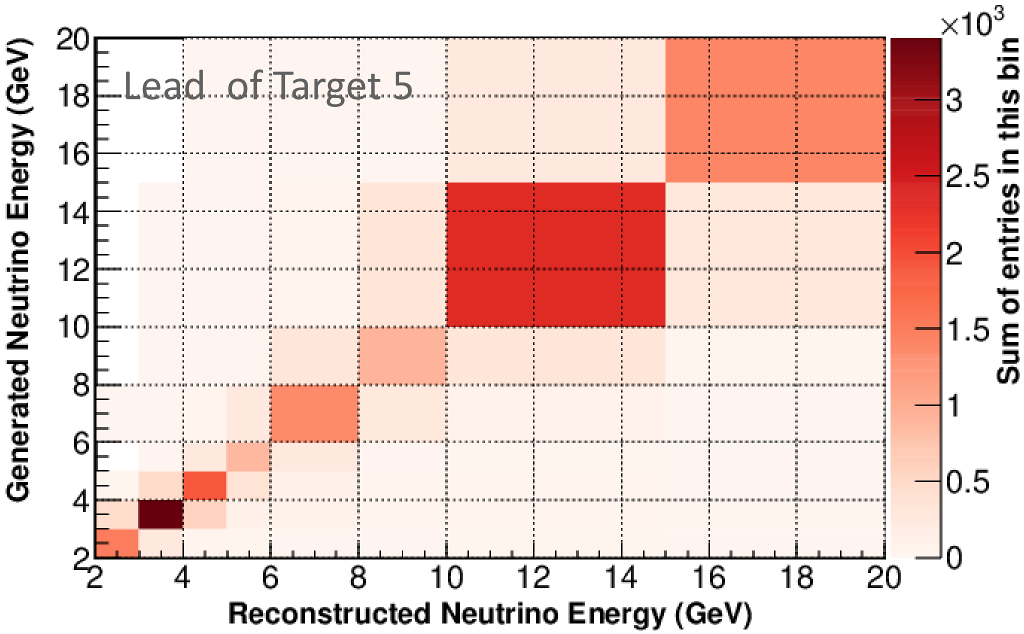
$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}$$

- $(d_j - b_j)$ — data – background = signal
- U_{ij} — Unfolding matrix
  - From reco bin j to “true” bin i
- ϵ_i — Efficiency for bin i
- (ΦT) — Flux times target number
  - Flux may depend on bin
- Δx_i — Bin width

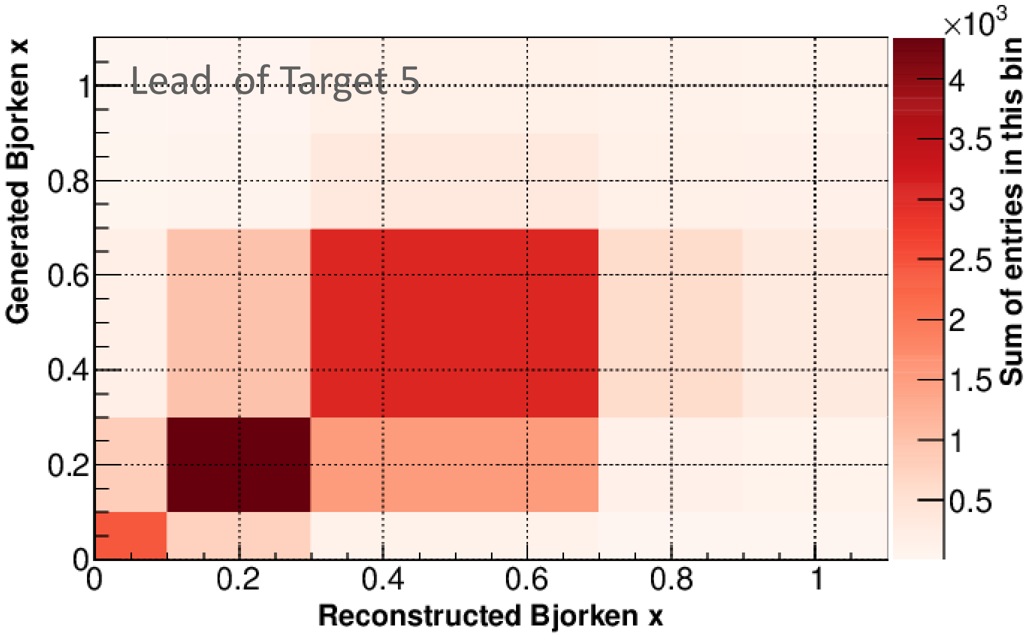
Bin Migration

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j \boxed{U_{ij}}(d_j - b_j)}{\epsilon_i(\Phi T)\Delta x_i}$$

- Unfold in neutrino energy
  - Iterative Bayesian unfolding with 4 iterations



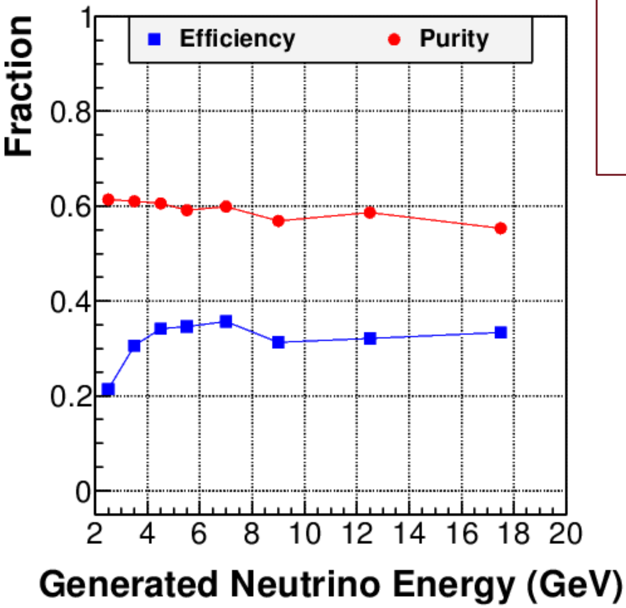
- Fold true x distributions
  - Multiply by this matrix →
  - Avoids model dependence
  - Migration in x is significant

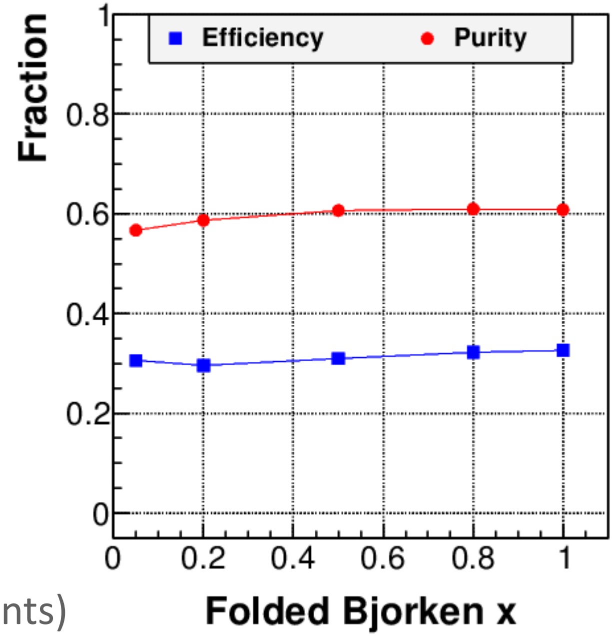


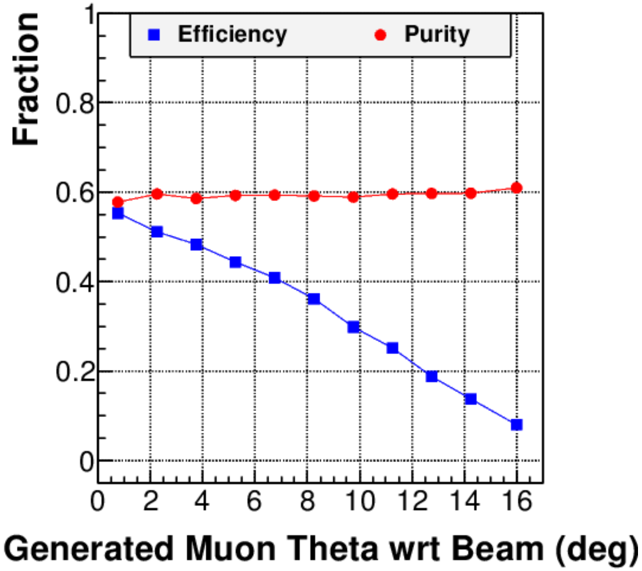
Reconstruction Efficiency

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\boxed{\epsilon_i}(\Phi T)\Delta x_i}$$

Signal Kinematics
(the "semi" in "semi-inclusive")
2 < Neutrino Energy < 20 GeV
0 < Muon Angle < 17 deg







MINOS-match requirement
Muon momentum threshold ~ 2 GeV

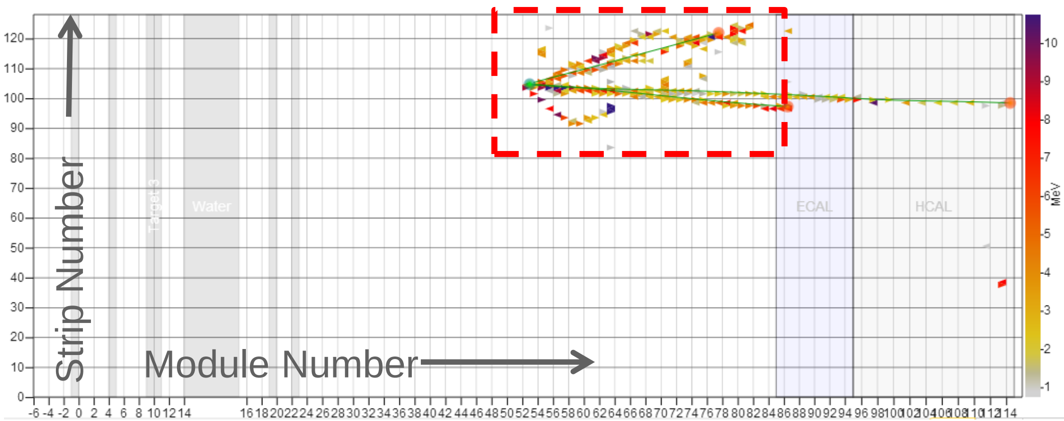
MINOS-match requirement
Geometric acceptance primary driver for efficiency loss
Angular threshold ~ 17 deg

(plots made with Target 5 lead events)

Subtract the Plastic Background

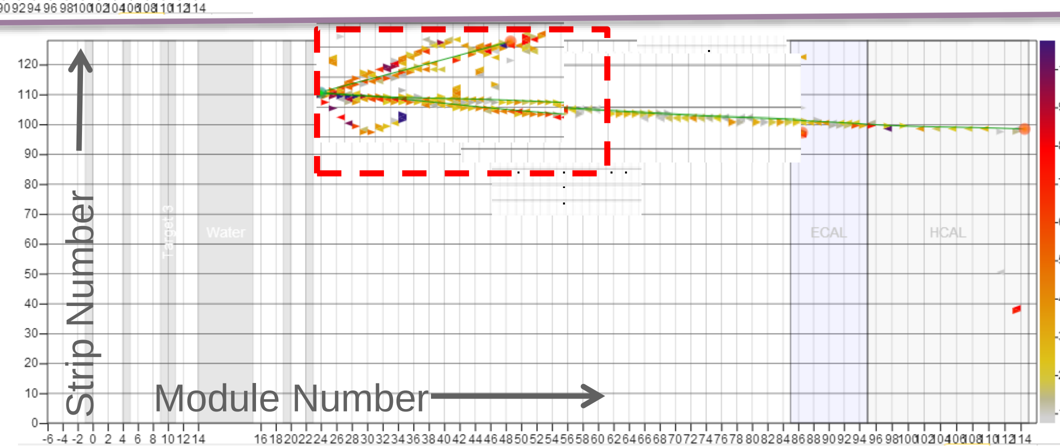
- Predict spectrum of background using:

Events in the Tracker | Geometric Acceptance | Reconstruction Efficiency



Found this event in scintillator of tracker

Pretend the same event happened in plastic background

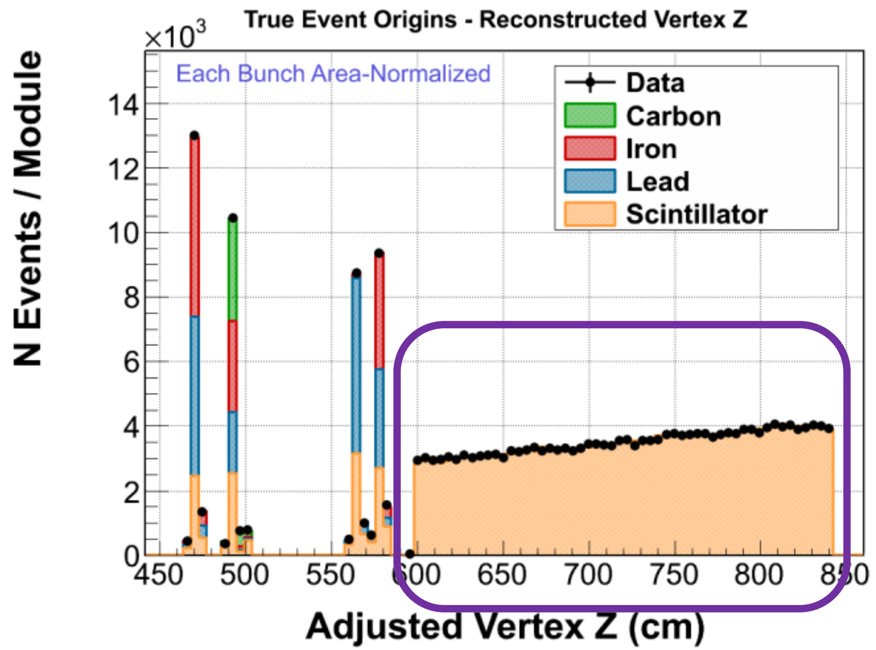


Predict spectrum of background using:

Events in the Tracker

Selection of events in tracker volume done in both data.
Does not use cross section model.

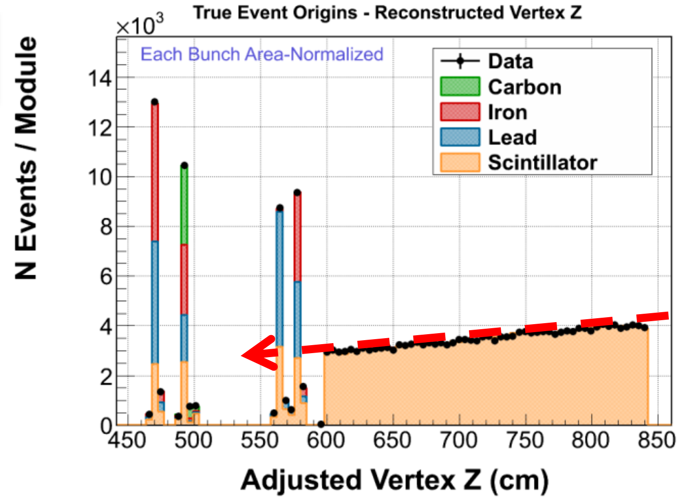
Data-driven background

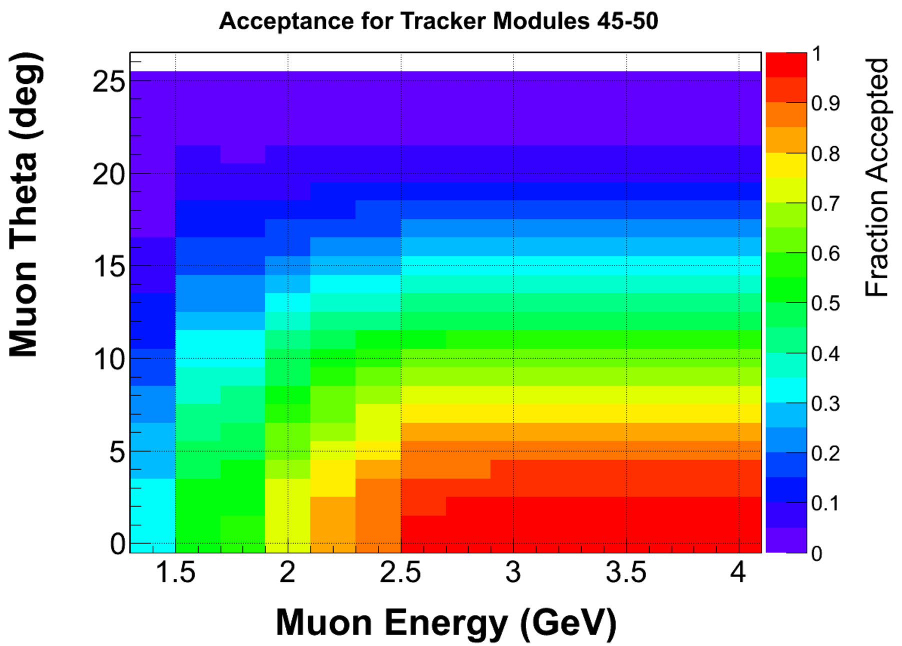


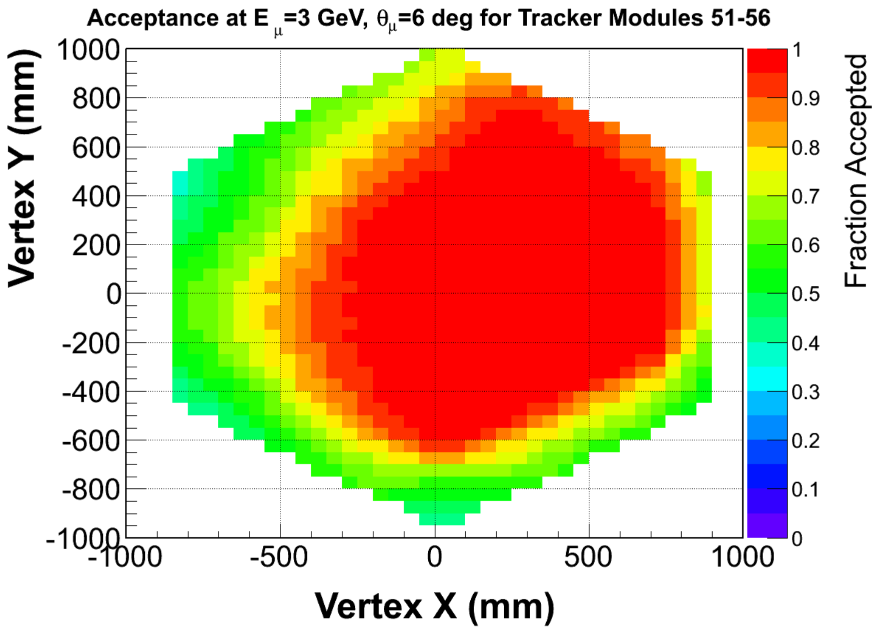
Predict spectrum of background using:

Geometric Acceptance

- Muon-only Geant4 simulation measures probability muon will hit MINOS
  - Function of muon energy, muon angle, vertex
  - Does not use neutrino interaction model







Predict spectrum of background using:

Geometric Acceptance

- Muon-only Geant4 simulation measures probability muon will hit MINOS
  - Function of muon energy, muon angle, vertex

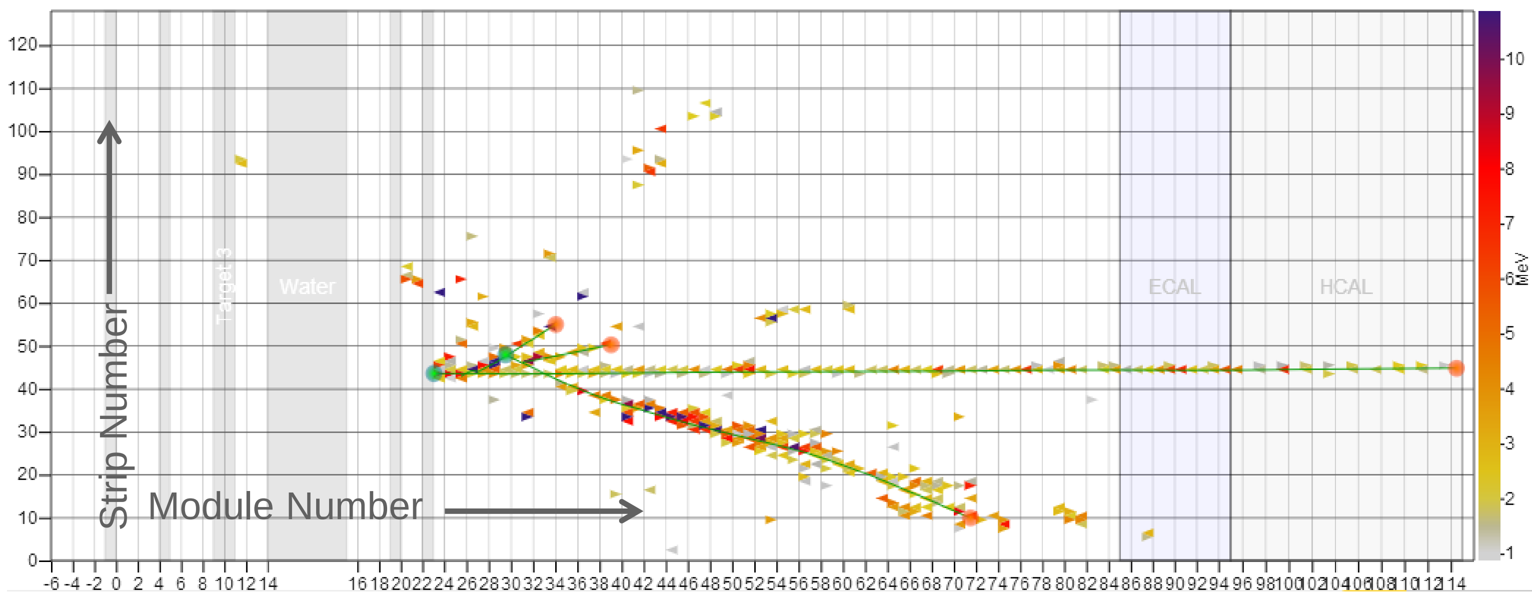
- Apply reweight factor to each event in tracker
  - “For every 1 event like this in the tracker, there will be X in the background”

$$RW = \frac{f_{acc}^{target}(E_\mu, \theta_\mu)}{f_{acc}^{tracker}(E_\mu, \theta_\mu)}$$

Predict spectrum of background using:

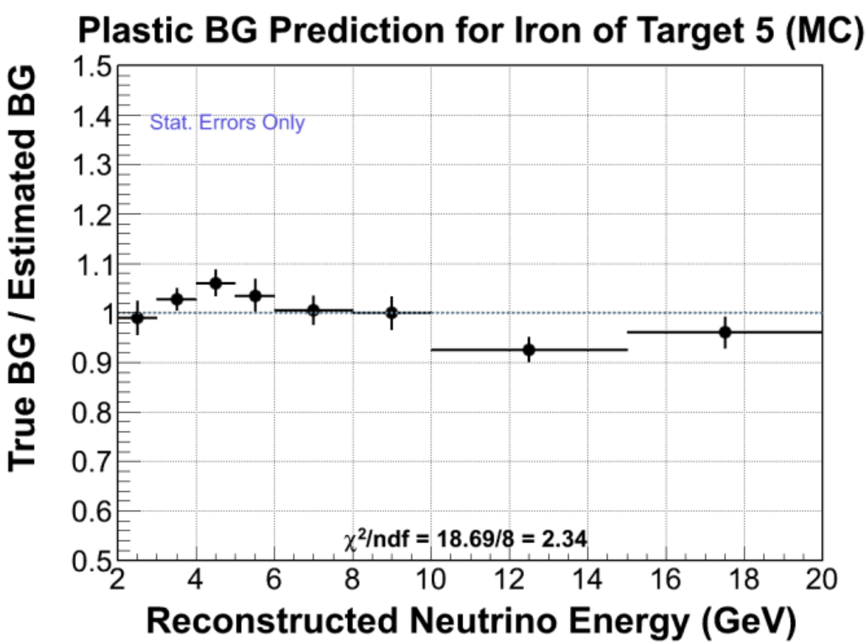
Reconstruction Efficiency

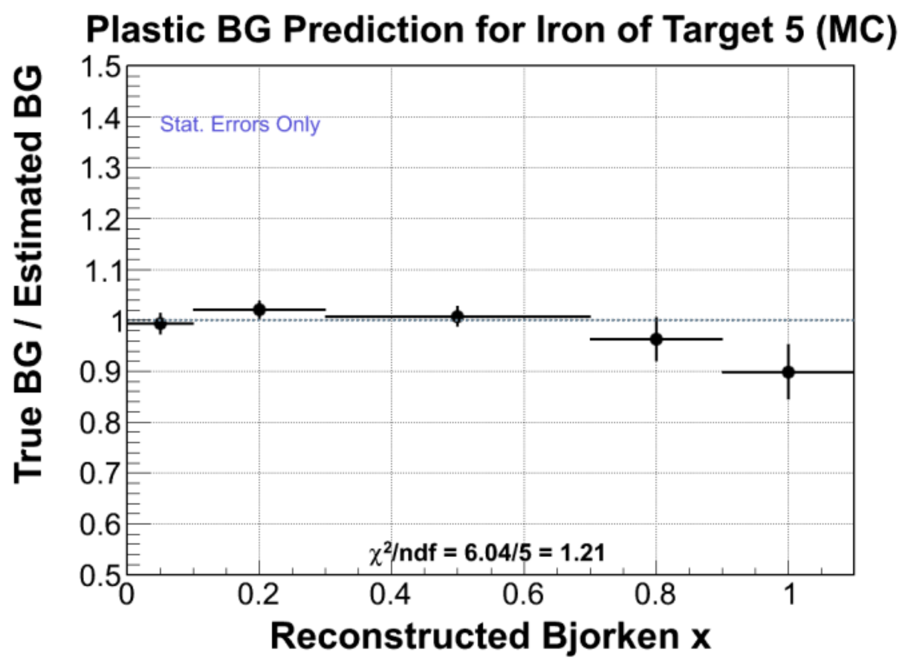
- Efficiency also depends on hadronic energy
  - Shower can obscure muon. Not addressed by geometric acceptance.
- Measure remaining efficiency with simulation
  - GENIE 2.6.2 and Geant4



Accuracy of Background Estimation

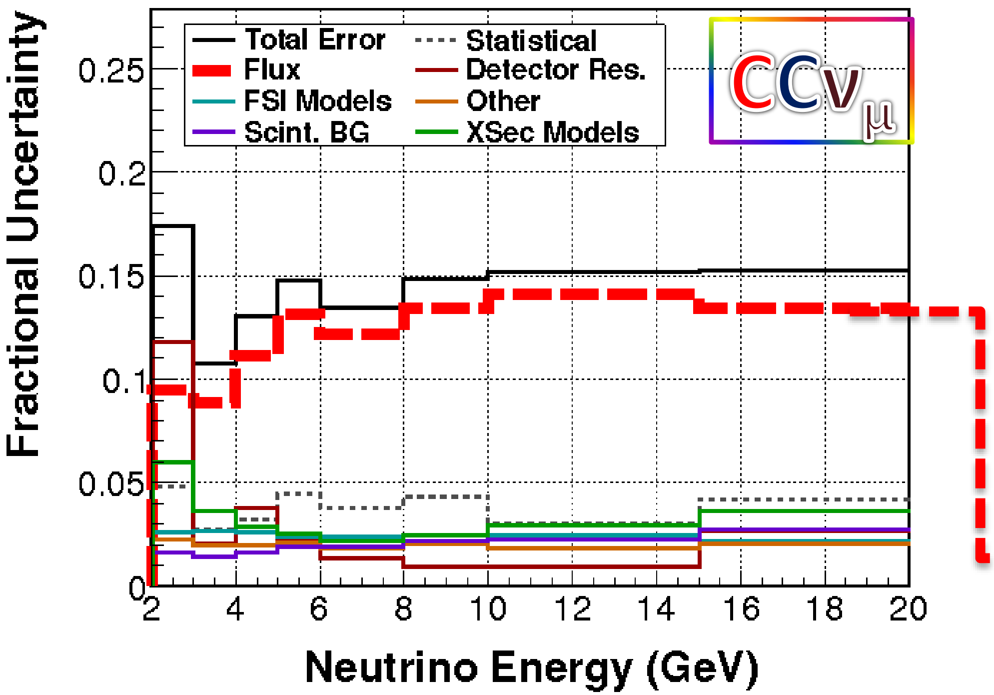
Events in the Tracker | Geometric Acceptance | Reconstruction Efficiency

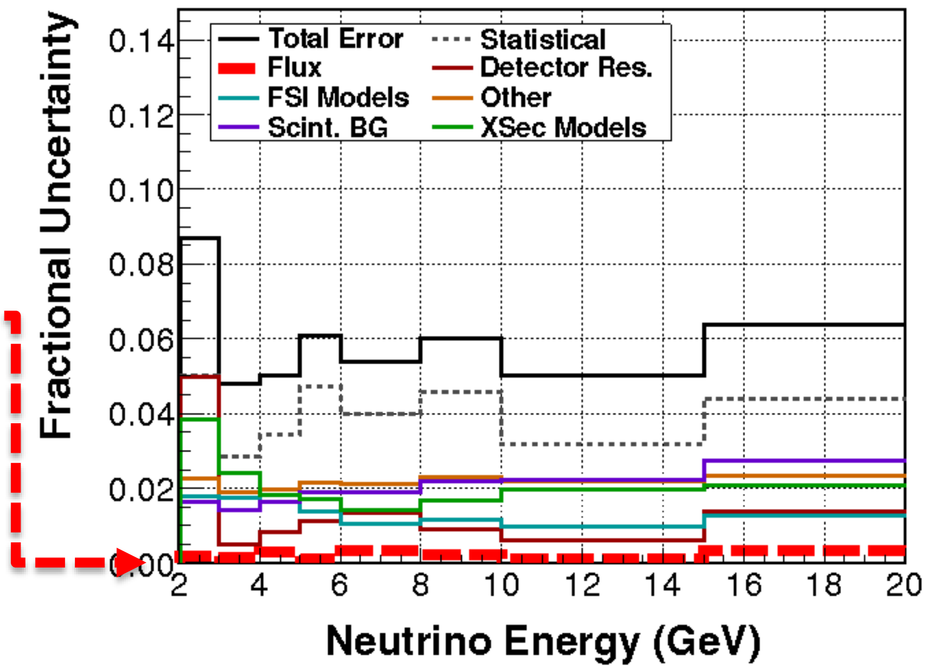




Errors on Absolute Cross Section

Errors on Ratio of Cross Sections





σ^{Fe}

$$\frac{\sigma^{Fe}}{\sigma^{CH}}$$

Form Ratios

- Combine targets
  - E.g. Add events from all lead pieces ***after*** efficiency correction
- Divide C, Fe, Pb cross sections by scintillator cross section
  - Each nucleus divided by a statistically independent scintillator measurements
  - Scintillator measurement is specific for each nucleus, to use the same transverse area